SOME COMFORT AND SAFETY ASPECTS OF URBAN WIND FLOW

VOLUME TWO

(Development of Pressure and Flow Patterns on Shopping Malls due to Natural Wind)

Eric W Marchant

Doctor of Philosophy : University of Edinburgh : 1975

DEVELOPMENT OF PRESSURE AND FLOW PATTERNS

ON SHOPPING MALLS DUE TO NATURAL WIND

CONTENTS

INTRODUCTION

This experimental investigation into the pressures created by natural air flows over buildings is a contribution to the definition and understanding of the problems of efficient smoke control using vent systems, especially for pedestrian malls in town centre redevelopments.

It is well known from the many studies carried out by the Building Research Station and other laboratories that the pressure distribution over the surfaces of bluff bodies in an air stream is far from uniform. It is equally well known that air travels down the vertical surfaces of buildings at velocities greater than the free air stream velocity. The results of such air movement may be discomfort to pedestrians and the generation of complex pressure patterns both on the building surface and the ground, or, in this case, the roof surface of malls within which may be hundreds of people. A knowledge of the pressure patterns on mall surfaces gives an indication of the effectiveness of simple roof vents as a smoke clearance technique for such large spaces. The aim of the work presented in this report is to ascertain which building geometries, such as may be found in town centre redevelopments, generate pressure patterns which would hamper, or affect adversely, the efficient operation of simple smoke vents. In general terms the surfaces of the mall roof which have negative pressure (Cp) values consistently, i.e. with all wind directions, are areas where roof/

roof vents can be located with confidence. However, vents placed in those areas which exhibit positive pressure values consistently could, if opened, allow the external air to descend into the smoke layers causing additional mixing of smoke and air. This may lead to a deepening of the smoke layer. Therefore, throughout the discussion of results it is assumed that positive pressures on the mall roof are adverse. Similarly, negative pressure areas on the mall sides are regarded as adverse for the air inlets.

The measurements were made in an open jet wind tunnel by using a pressure probe (see Appendix A) placed on the surface of the mall models. The use of the simple probe gave flexibility in location of measurement points and in the subsequent data translation.

The mall models were simple wooden blocks, either solid or plywood boxes, with side to side unit ratios of 2·5 : 10; 5 :10; and 7·5 : 10; the height being kept constant at 1 unit. The real dimension of 1 unit is 50 mm. Pressure measurements were made on a 50 mm grid over the mall "roof" and "sides" generally, but in a few cases it was decided to measure at 25 mm intervals, especially near to the base of the model buildings.

Although it could have been possible to omit some measurements on geometries where axial symmetry existed, with respect to the wind/

wind flow, this was not done except in those areas of Geometry 18 which are remote from the effects of the courtyard and the sides of the mall. These areas were assumed to have the same pressure patterns as Geometry 15.

The three-dimensional relationships of the blocks chosen for each geometry can be seen readily by observing a pressure contour diagram and its corresponding flow diagram at one time. The number on the block in the pressure diagram gives the height of the superimposed block in units of 50 mm.

RESULTS OF THE PRESSURE MEASUREMENT ON MALL SURFACES.

The results of the pressure measurements on the model malls are presented in Figures 1-74 as pressure coefficients (Cp). Each diagram shows the plan of each geometry with the adjacent sides developed. The pressure coefficients on the plan of the mall are presented as contours of equal pressure, whilst the sides have a number of points where the pressure coefficient at that point is given.

Where there are "buildings" on top of or adjacent to the mall, these are outlined by a thick solid line and the enclosed number indicates the height of the "building" in numbers of units as defined previously.

The wind angles are given in degrees, with the 0^{o} wind moving from left to right and the angles are measures in an anti-clockwise direction. For reference a diagram of the wind directions is given before the pressure figures.

The results are described in series of similar geometries. Each set of similar geometries is discussed by wind direction.

Throughout/

Throughout these descriptions it should be remembered that for effective smoke control in the mall volume, negative pressures are sought on the "roof" and positive pressures on the sides.

1. Comparison of Geometries 1, 3 and 15

These geometries are models of the three basic malls.

270° Wind (Figs. 3, 9 and 60)

Windward Side

All the values of the pressure coefficient are of the same order. The variation at ends of the side are due to the non-uniform air flow over and round the model.

Sides parallel to Wind

As these sides are lengthened the flow regime is modified, along the length, although the generation of negative pressure at the ends is maintained. Because of the flow modification a positive pressure area is formed in the mid-section of the sides in Geometry 15 (Fig. 60).

Leeward Side

The values of the pressure coefficient for each of the geometries are similar. The small variations being due to the non-uniform flow over the model.

Plan/

Plan

The three geometries show a consistent pressure pattern at the leading edge and a development of pattern according to plan proportion.

0^{o} Wind (Figs. 1, 7 and 58)

Sides

For all the sides of these geometries, patterns similar for those with the 270^{o} wind are generated. The appearance of the positive pressure areas on the sides parallel to the wind reinforces the previous comments that the length of side is important in the generation of the positive pressure area. An enclosed volume of plan ratio 5 : 5 units and 1 unit high could have negative pressures on three sides, the value of which could equal most of the negative values recorded on the roof. A comparison of the previous wind direction (Figs. 3, 9 and 60) with the present direction, suggests that shape has an important influence on the distribution of positive and negative pressure on the sides.

Plan

Fig. 1 (Geometry 1) when compared with Figs. 7 and 58, clearly shows the end effects due to the small dimension of the windward end. As in the previous comparison, the plans show similar pressure patterns, especially those for Geometries/

Geometries 3 and 15. The large area between the -0·25 contours has a pressure coefficient value between -·025 and zero.

315° Wind (Figs. 2, 8 and 59)

The Windward Sides

These sides have large areas of positive pressure and the value of the pressure coefficients increase with the increase in size of the model. At the leeward end of each side there is an area of negative pressure, this is a feature which is repeated on many other geometries, especially on the short sides. Another feature which will recur is that the positive pressure at the lower edge of the side is greater than the positive pressure at the corresponding point on the upper parts. Similarly the negative pressure at lower points has usually a lesser value than the corresponding points on the upper parts.

Leeward Sides

These exhibit a progression which may be due to the length and size of the model,as an examination of Fig. 59 shows areas of positive pressure on the leeward ends of the sides. An examination of the detailed results for these sides showed a progressive decrease in negative pressure at the leeward end of Geometry 3 which turns into a positive pressure in Geometry 15. This result is due to the way the wind flows over the broadest model and moves round its sides.

Plan/

Plan

The general flows have a progressive pattern where the pressure coefficient contours change to become nearly parallel to the wind flow(Geometry 15). (It is possible that a square model of the same height would have pressure contours more parallel to the direction of the wind flow).

2. Comparison of Geometries 1 and 2

These geometries are the basic mall of plan ratio 10 : 2·5 and the same mall with a 2 unit high building placed on its centre line.

0^{o} Wind (Figs. 1 and 4)

Sides

The windward side shows a slight increase in positive pressure. On the sides parallel to the wind flow, the area of positive pressure has been brought towards the wind and its size reduced, although its spot pressure coefficient is greater than that in Geometry 1. The pressure coefficients on the leeward side show little difference.

Plan

The introduction of the building has changed the pressure pattern significantly. To the leeward a negative pressure regime has been established and to the windward a large area of/

of the roof surface has positive pressure. It was observed, at the windward edge, that the negative pressure was reduced.

315° Wind

Windward Side

The short windward side shows little difference with the building added to the mall. The long side shows an increase in the area of negative pressure and the positive pressures were increased significantly, especially near the foot of the building. With the wind in this direction the building has a marked influence on the pressure regime on the long side.

Leeward Side

On the long side the negative pressures are increased in the wake of the building, due to the added turbulence generated by it. The other areas of the leeward side show little difference in their pressure coefficient values. There is no significant change in the overall pressures on the short side.

Plan

The introduction of the building altered the pressure pattern and created a small area ofpositive pressure to its windward. (The implication of these changes will be discussed later).

Moving/

Moving away from the building on this side, the change in difference of the pressure coefficient is reduced and the -0·75 contour is moved only a small distance. On the leeward side of the building, the area has increased negative pressures.

270° Wind (Figs. 3 and 6)

Sides

In this case the windward side has increased positive pressure near the foot of the building. The leeward side has increased negative pressures in the wake of the building, but the short sides, parallel to the wind, do not show any significant changes in pressure coefficient.

Plan

There was a general but slight increase in negative pressure over the whole of the mall roof surface but the introduction of this building does not make any significant changes to the pressure pattern. (Geometry 1).

3. Comparison of Geometries 3, 6, 5 and 4

These geometries were selected as a group because they are the same height (4 units) and change in width across the larger basic mall (plan ratio 10 : 5).

0° Wind (Figs. 7, 16, 13 and 10)/

0^o Wind (Figs. 7, 16, 13 and 10)

Windward Side

As the building increases in width there was a corresponding increase in positive pressure on this side.

Leeward Side

The introduction of the Geometry 6 building reduces the negative pressure and this is a result of the plan pressures being displaced to the leeward. The wider buildings of Geometries 5 and 4 increase the negative pressures on this side.

Sides Parallel to the Wind

For Geometry 6 the positive pressure area on this side is increased both in area and in value and the value of the negative pressures is reduced. In Geometries 5 and 4 the area of positive pressure is reduced considerably and the value of the negative pressure areas is increased due to the downflow of air round the building.

Plan

Comparing Geometries 3 and 6 (Figs. 7 and 16), it is shown that the small building created a large area of positive pressure to the windward. Considering Geometries 5 and 4 (Figs. 13 and 10) the positive pressure area is slightly enlarged but the pressure gradients become steeper progressively.

To/

To the lee of the buildings the pressure pattern in Geometry 5 (Fig. 13) is a development of the pattern for Geometry 6. In both cases the air flow passing the building is able to affect the pressure pattern directly. The air flow for Geometry 4 (Fig. 10) is different due to the building spanning the whole width of the mall, thereby deflecting the wind down and along the long sides of the mall. This explains the higher negative pressure on the mall sides. The area to the lee of the building in Geometry 4 (Fig. 10) has a reasonably constant negative pressure which may be due to the air streams around and above the space forming a large scale slow moving vortex.

315° Wind (Figs. 8, 17, 14 and 11)

Short Windward Sides

There is no large variation in the pressure patterns or the pressure coefficient values on these sides. This was not unexpected as this is the side which is unaffected by the building as it faces into the wind directly.

Long Windward Side

There is little change in the pressure pattern comparing Geometries 3 and 6, but there is a progressive change for Geometries 5 and 4. The zero contour is shifted to the windward and the positive and negative pressures are both increased in value.

Leeward Side/

Leeward Sides

Again there is little change between Geometries 3 and 6 but the pressures with the wider buildings are increased in negative value.

Plan

On the windward side of the building even the introduction of the small building in Geometry 6 has created an area of positive pressure which is increased in extent and value for each of the wider buildings. The pressure gradients for Geometries 5 and 4 are somewhat similar. Considering the leeward side of the building, the introduction of the building in Geometry 6 has created higher negative pressure values except that the far leeward corner shows little change when compared to the contours in Geometry 3. Geometries 5 and 4 show a pressure pattern which increases in negative value with the width of the buildings. The distortion of the contours in Geometry 4 are due to the wind being unable to flow around the end of the building at the mall roof level.

270° Wind (Figs. 9, 18, 15 and 12)

Windward Side

From an examination of the detailed results there was some variation of the pressure patterns on this side and as expected higher positive pressures were recorded below the building in Geometry 4, in fact the presence of the buildings in/

in Geometries 5 and 6 also influence the pressure on this side. All the sides exhibit the phenomenon that all the lower points give greater positive pressure than the corresponding upper points.

Short Sides (Parallel to Wind)

In general, these sides for all these geometries show a negative pressure régime. The appearance of the positive pressure areas on Geometries 5 and 6 are repeated in other geometries and it may be that the pressures presentedin Figs. 9 and 12 may be too negative.

Leeward Sides

All four geometries give a negative pressure pattern, there being little difference between the top and bottom points and a region of higher negative pressure is created by the building in Geometry 4 only.

Plan

Comparing Geometries 3, 5 and 6 (Figs. 9, 18 and 15) the buildings cause a small area of positive pressure to their windward. This effect is shown also in Geometry 4 (Fig. 12) by the increase in positive pressure on the windward side of the mall at the foot of the building. The majority of the roof surface is under a negative pressure regime whose values are similar to those in other geometries. However, it is interesting to note that the pressure patterns are less altered with the wider building. This is due to the absence of end effect for Geometry 4.

4. Comparison of Geometries 3, 9, 8 and 7

This group of geometries has the same plan arrangement but the height of the building is changed from 2 to 4 to 6·5 units high.

0^{o} Wind (Figs. 7, 29, 24 and 19)

Windward Sides

With an increase in building height there is also increases in the positive pressure coefficient values on this side.

Leeward Sides

On these sides there is a marked increase in the value of the negative pressures. This increase in negative pressures is much greater than the corresponding increase in positive pressure values found on the windward sides.

Sides Parallel to the Wind/

Sides Parallel to the Wind

The effect of raising the height of the building on the pressure patterns on these sides is significant. The negative pressure area at the windward end is reduced progressively. There is an increase in the value of positive pressures. In addition, the negative pressure region at the leeward end remains reasonably constant in area although the values of the pressure coefficient are increased with increasing building height.

Plan

A strong positive pressure is developed for all building heights and this covers nearly all of the roof surface: with increasing building height the pressure gradient becomes steeper. Small areas of negative pressure are present near the ends of the building in each case. These are due to the air flow being deflected around the ends of the building and the pressure coefficient values increase in a negative sense with increasing building height.

315° Wind (Figs. 8, 30, 25 and 20)

Windward Sides

There is a slight progressive increase in the values of the positive pressure coefficient and a corresponding increase in the negative pressures at the leeward end of the long side can be observed.

Leeward Sides/

*@

Leeward Sides

As in the previous wind direction, the values of negative pressure increase with the increase in building height.

Plan

Here the pressure patterns exhibit a simple progression with the area of positive pressure being increased with the corresponding increases in building height. The differences in pressure gradient are small when compared with those in the previous wind dire ction.

270° Wind (Figs. 9, 31, 26 and 21)

Windward Sides

There is little change in the pressure regime except near the foot of the building and here the negative pressure is increased.

Leeward Sides

Again there is little change except that the negative pressures behind the building are increased slightly.

Sides Parallel to the Wind

On the side remote from the building there is no significant change in the pressure pattern. However, on the sides adjacent to the building there is a marked increase in negative pressure at the windward ends but the values of pressure coefficient at the leeward ends are little changed.

Plan/

Plan

It appears that the building has little influence on the shape or values of the pressure contours. This is similar to the effects observed for Geometry 4 in Fig. 12.

225° Wind (Figs. 8, 32, 27 and 22)

Windward Sides

The positive pressure area on the short sides is similar for each geometry and there is an increase in the values of the pressure coefficient with the building in position. On the long side the values of the negative pressures on the upper part are increased by the presence of the building. A detailed examination of the results shows that the positive pressures measured on the upper parts of this long side in Geometry 3 have very low value so the shift in the zero contour is not large.

Leeward Sides

The pressure regime on the short sides is little altered. The presence of the building has little effect on the pressure values on the long side except that the negative pressures have higher values near the foot of the building in Geometry 7 (Fig.22) This latter observation is expected due to the greater disturbance to the windflow by this tall building.

Plan/

Plan

All the geometries with buildings in this group induce a negative pressure system on the mall roof. These systems have values considerably greater than those measured for Geometry 3. These pressure patterns appear to be influenced by the air flow round the buildings so that a "strong" pattern is induced in Fig. 22 (Geometry 7).

180° Wind (Figs. 8, 33, 28 and 23)

Windward Sides

The area of positive pressure is similar for each of these geometries and each increase in building height gives a corresponding increase in the values of the pressure coefficients. The small areas of negative pressure are due to the air flowing down and round the building.

Leeward Side

Comparing Geometries 3 and 9 there is little change in the pressure regime. Considering Geometry 8, the positive pressure area may be explained by the different nature of the flow over the trailing edge of the mall (See Fig. 128) A negative pressure regime is regained in Geometry 7 (See Fig. 123) It should be noted that the appearance of the positive pressures in Geometry 8 is a function of the specific geometrical relationship and if the mall to the leeward side of the building was shorter the pressure pattern would approach that observed in Geometry 4 (Fig. 10)

Sides Parallel to the Wind/

Sides Parallel to the Wind

On these sides the positive pressure area is shifted progressively with the direction of air flow. The negative pressure values increase in the vicinity of the building.

Plan

A general comparison of the flow geometries in this group shows a progressive increase in the negative values of the pressure coefficient with the increase in height of the building.

In Fig. 33 the zero contour is the area of transitional flow beyond which the air flow is little disturbed by the building. Reference to the flow diagrams for Geometries 8 and 7 (Figs. 128 123) indicate that the points of transitional flow are shifted progressively to the windward.

The effect of building height on the pressure values is shown clearly in the areas adjacent to the buildings where the increase is from -1·0 in Geometry 9 to - 3·0 in Geometry 7. The increase in pressure coefficient is due to the larger building displacing greater volumes of air, the greater the displacement the greater the relative speed, therefore higher negative pressures will be induced.

There is an area of reasonably constant pressure behind each of the buildings whose extent is roughly proportional to the effective height of the building, i.e. building + mall. This is caused by, or due to, a slow moving mass of air in the wake of/

of the buildings which is enveloped by the rest of the air stream.

5. Comparison of Geometries 3, 12 and 13

Geometries 12 and 13 are similar in that they do not have buildings on the top of the mall surface but have an adjacent building (Geometry 12) or a proximate building (Geometry 13)

315° Wind (Figs. 8, 47 and 51)

Windward Sides

On the short sides there is, as expected, little variation in the pressure regime for each of these three geometries. For the long sides a comparison of Figs. 8 and 51 show little change in the values of the positive pressure but the increased air flow between the proximate building and the mall causes the negative pressure area to increase in both size and value of the pressure coefficient. Considering Fig. 47 (Geometry 12) the adjacent building has created comparatively high positive pressures in its vicinity, but the pressures to the windward end of the side are similar to those found in Geometries 3 and 13.

Leeward Sides

Comparing the short sides, it can be seen that the adjacent building in Fig. 47 has a marked influence on the negative pressures, due to this side being in the direct wake of the building. Geometry 13 shows little difference in measurement to those for Geometry 3.

The/

The values of the pressure coefficient on the long sides show little variation between these three geometries.

Plan

The disturbance of the pressure pattern in Fig. 47 is similar to that found for Geometry 5 (Fig. 14). Although there is a fairly steep pressure gradient developed, the effect of the building is clearly limited. The building in Geometry 13 (Fig.51) has a limited effect on the pressure pattern also and the increase in negative pressure coefficient value is less than that found for Geometry 3 as would be expected, because of the greater distance away from the roof surface of this particular building.

270° Wind (Figs. 9, 48 and 52)

Windward Side

In Fig. 48 there is a small region of increased positive pressure adjacent to the building. Because of a local disturbance in flow a less positive area, compared with that in Geometry 3, is induced along the top edge. The pressures away from the building are less than those found in Geometry 3 and it was observed that part of the air flow was travelling away from the building at right angles to the main wind flow at low level.

For Geometry 13 there is a negative pressure area in the wake of the building (Fig. 52) and the reduction in positive pressures is similar to that found for Geometry 12.

Sides Parallel to the Wind/

Sides Parallel to the Wind

There is little difference in the pressure regimes for these sides except for the one which is nearest to the building in Geometry 13. Here the effect is only to reduce the value of the negative pressures at the windward end.

Leeward Side

On all these sides a negative pressure regime is maintained but there are some variations in the values of the pressure coefficient which may correspond to the changes in pressure pattern on the plan.

Plan

The pressure patterns for Geometries 12 and 13 have an increased gradient compared with that for geometry 3. The greatest negative value of the pressure coefficient are somewhat increased due to the increased flow of air over the surface.

225° Wind (Figs. 8, 49 and 53)

Windward Sides

A comparison of Geometries 3 and 12 for the short sides shows that the flow adjacent to the building has created a negative pressure area at the upper edge of the sides. For Geometry 13 the pattern is similar to that for Geometry 3 but the values of the pressure coefficient are reduced.

On the long side of Geometry 12 the building has created a negative pressure area to its lee side and the remaining positive pressure area has increased value of pressure coefficient. For Geometry 13 again the building has created an area of negative pressure to its leeward due, in part, to the channelling of the air flow between the building and the mall surfaces. Here the values in the positive pressure area are increased.

Leeward Sides

On the short sides the pressures in Geometry 12 are little different to those in Geometry 13, but for Geometry 13 the values of the negative pressures are reduced slightly although the pressure pattern is similar.

In all three geometries the pressure pattern found on the long sides is similar but the pressure coefficient values in Geometry 3 are consistently greater than those found in Geometries 12 and 13.

Plan

Both buildings produce areas of negative pressure which have greater value than those in the same areas for Geometry 3. The building in Geometry 12 and an adjacent area where a high pressure is induced and the pressure gradient is greater than on the corresponding areas found in Geometry 13. However, the effect of both buildings is limited and large areas of the mall roof show a pressure regime similar to that found for Geometry 3.

90° Wind (Figs. 9, 50 and 54)

Sides

The pressure patterns are similar for each geometry but the building ends in Geometries 12 and 13 show some increase in the values of pressure coefficient.

Sides Parallel to the Wind/

Sides Parallel to the Wind

Comparing Geometries 3 and 12 little change is observed on the side away from the building but the side adjacent to the building exhibits a definite area of positive pressure and the values of the negative pressure area are increased at the leeward end.

For Geometry 13 the area of positive pressure on the side nearest the building is increased both in size and pressure value, although the windward end has a pressure pattern similar to that in Geometry 12.

Leeward Side

The building in Geometry 12 has induced greater negative values of pressure coefficient. However, the pressure regime in Geometry 13 is quite different. The positive pressure area near the building is due to the pressure build-up in front of it but the positive pressure area at the end away from the building appears to be inconsistent with other measurements.

Plan

Both buildings have a marked effect on the pressure regime. A positive pressure area is developed to the windward of each building, the higher value being recorded for Geometry 12. The effects are limited as the pressure contours away from the building regain a pattern similar to that in Geometry 3.

6. Comparison of Geometries 3, 4 and 14

Geometries 4 and 14 have a building in the same location and of the same overall height but in Geometry 14 the building has a slot 0·5 units high at ground level.

0^{o} Wind (Figs. 7, 10 and 55)

Windward Side

All sides maintain a positive pressure regime; the values of the pressure in Fig. 10 are greater than those in Fig. 7, as described previously. The measurements of Geometry 14 show that the values are reduced when compared with Geometry 4. This may be due to the fact that the air flow is able to flow under the building reducing the positive build up to the windward side of the building.

Leeward Sides

The difference between Geometries 4 and 14 is that the pressure at the leeward edge of the roof of the mall are less for Geometry 14 than those for Geometry 4 and this corresponds with the difference in pressure coefficient values on the leeward sides.

Sides Parallel to the Wind

Here the pressure pattern is similar for Geometries 4 and 14, i.e. the positive pressure area is shifted to the windward when compared with Geometry 3.

The/

The negative pressures to the lee of the building are less in Geometry 14 than those in Geometry 4. This is due to a proportion of the air flow being deflected along the sides in Geometry 4 whereas in Geometry 14 the slot under the building allows some of this air to flow directly.

Plan

In Geometry 14 (Fig. 55) the windward side shows a strong positive pressure pattern with overall values similar to those found for Geometry 4. The shape of these contours is changed due to the air flow being able to flow under the building for Geometry 14. At this point the pressure changes from positive to negative in a small distance; the accelerated flow generating a very steep pressure gradient, the values of which vary from + 1·5 to - 3·0. To the lee of the buildings there is a definite pressure pattern (and the pressure gradient diminishes in value towards the lee side) for Geometry 14.

3I5° Wind (Figs. 8 11 and 56)

Windward Sides

On the short sides the pressure pattern is similar for all three cases but the leeward end positive pressure coefficient values in Geometry 14 are a little higher than the others. On the long sides the shift in the zero contour is maintained: the value of the pressure coefficients for Geometries 4 and 14 are similar, but with minor variations, for both positive and negative pressure regions.

Leeward Sides/

Leeward Sides

On the short sides the negative pressure regime is maintained for all three geometries and the values found for Geometries 4 and 14 are similar.

However, the pressure coefficient values on the long sides show some major changes. Although the reason for the difference between Figures 11 and 56 are not clear, the change in air flow pattern due to the slot under the building will influence this pressure regime.

Plan

There is a similarity between the windward pressure pattern for Geometries 4 and 14 but the flow under the building (Fig. 56) induces a steep pressure gradient at this point. Again the pressure coefficient values are similar to the leeward but a strong pattern is induced for Geometry 14.

270° Wind (Figs. 9 , 12 and 57)

Windward Sides

A mainly positive pressure pattern is maintained in all three geometries. The buildings in Geometries 4 and 14 create an increase in positive pressure in their vicinity and the values on the sides for these geometries are similar.

Leeward Sides

Comparing Figs. 12 and 57, there is little difference in the pressure regime except that the values are less negative in the wake of the Geometry 14 building.

Sides Parallel to the Wind

These sides on Geometry 14 show a similar pressure pattern to those for Geometry 4 although the values are less negative.

Plan

Again, comparing Geometries 4 and 14, there is a remarkable similarity in the pressure regime and the influence of the slot under the building is indicated by the reducing negative pressures at its windward end.

7. Comparison of Geometries 3, 10 and 11

This group of geometries is more complex than any of the preceding groups in that Geometries 10 and 11 have more than one building on top of the mall. Because of the differences between Geometries 10 and 11, these are discussed separately, but first some points of similarity are noted.

Similarities between Geometries 10 and 11

For the zero degree wind direction (Figs. 34 and 39) the pressure patterns and pressure coefficient values of the windward sides and the windward edges of the mall roofs are similar.

Considering Figs. 35 and 40 (315^{o} Wind) there is a similarity between the pressure patterns and the pressure coefficient values for the windward side. On the plan the pressure pattern around the bigger building, for both geometries, is similar, although there are differences in the measured pressure values.

Considering Figs. 36 and 41 (270° Wind) the similarities are found on the windward side, the area of the mall roof to the windward and the leeward sides of the bigger building. In addition there is a negative pressure regime maintained on the leeward sides of the mall and its roof.

For the 225° Wind (Figs. 37 and 42) there are a number of similarities. First the sides are similar except those areas adjacent to the smaller building in Geometry 10. Secondly, the areas of the mall roof around the bigger building show marked similarity both in terms of the pressure pattern and the measured values.

For the 135° Wind (Figs. 44 and 37 reversed), similar pressure patterns are shown around the bigger building and the sides of the mall. These results compare with those in Fig. 42 (Geometry 11).

Comparing Figs. 45 and 36, (90° Wind) there are similar pressure patterns and measured values for the sides and roof of the mall around the bigger building and these results compare with those in Fig. 41.

The similarities found for the 315° wind are repeated when comparing Fig. 46 (Geometry 11) and Fig. 35 (Geometry 10). There is a vast similarity between Figs. 40 and 46 (both Geometry 11) as would be expected.

8. Comparison of the effects of different wind direction on Geometries 10 and 11 (Figs. 34 - 46 inclusive)

In the following notes the axial wind is taken to be that at 90° to either axes of the models and the oblique wind is taken to act at 45° to either axes of the models.

Sides

With an axial wind the sides of the model show a positive pressure pattern to the windward although there are small negative areas at the ends. The other three sides show a pressure pattern which is predominantly negative. The obvious exception to these regimes is found in Geometry 11 with the 180° wind (Fig. 43). Here the pressure pattern of the windward side and the windward end of the long side show a pattern similar to that found in Geometry 3 (Fig. 7) This is due to the absence of buildings near the windward edge of the mall.

The oblique winds create positive pressures on the windward sides except for small negative areas at the leeward ends. The leeward sides are all within the negative pressure regime. These effects are common to all of the geometries described to this point, but with variations in the shape of the areas and in the pressure coefficient values, which are due to the location of the buildings with respect to the mall sides. It should be noted that in general all the upper parts of the mall sides have pressure coefficient values less positive for more negative than the points directly below at the lower part of the side.

Plan (Geometry 10)

For the axial winds (Figs. 34, 36 and 38) there are areas of positive pressure created to the windward of the building. Considering Figs. 34 and 38, a negative pressure area is found in the lee of the windward building. The contours in Fig. 38 bear some resemblance to those found in Fig. 13 (Geometry 5) and this similarity may be due to the air being able to flow around the windward building in each case. This is borne out by the contours in Fig. 10 (Geometry 4) where the air flow is reflected down, away from the mall roof.

On the long axis of Figs. 34 and 16 (Geometries 10 and 6) the contours behind the building are similar. This may be due to the near square plan shape of the windward building in each case.

Again comparing Figs. 34 and 38, the positive pressure patterns to the windward of the leeward building are similar.

Comparing Figs. 35 and 37 (315° and 225° wind) there are positive pressure areas to the windward of the bigger building and in Fig. 37 this changes to a negative pressurepattern in the lee of the smaller buildings and relatively high negative pressures are developed in the wake of each building.

Plan/

Plan (Geometry 11)

Considering Figs. 39 and 46, it is apparent that the contour pattern is related directly to wind direction.

It may be noted that steep pressure gradients exist between the buildings in Fig. 40 - 44 and 46. A simple superimposition of pressure contours for Geometry 11 shows that the majority of the roof area is in a positive pressure regime for all wind directions, and only a very small part of the roof remains in the negative pressure area and this would disappear with a slight shift in position of the buildings. The same exercise for Geometry 10 shows that two areas remain in a negative pressure regime when all wind directions are considered. These are the small section between the small building and a more extensive area in the middle of the plan (Fig. 95).

9. Comparison of Geometries 15, 16 and 17

This group of geometries have the common mall size which has a plan ratio of 7·5 to 10. The buildings in Geometries 16 and 17 have the same plan shape but both buildings in Geomtry 16 are six units high whereas in Geometry 17 one of the buildings is two units high only

0^{o} Wind (Figs. 58, 61 and 65)

Windward Sides

In Geometries a 16 and 17 a small negative pressure area appears at the ends of these sides which is due to the strong return/

return flow of the face of the windward building. Otherwise a positive pressure regime exists and the values recorded in Figs. 61 and 65 are higher than the corresponding figures recorded for Geometry 15. It is interesting to note that the zero contours match with those of the windward edge of the mall roof.

Leeward Sides

These sides maintain a negative pressure regime and the pressure coefficient values increase with respect to building height.

Sides Parallel to the Wind

Pressure patterns in Geometries 16 and 17 are similar but they have little in common with that found in Geometry 15. (Fig. 58). The high negative pressures are due to the down flow of air from the windward of the building. The pressure coefficient values in Geometry 16 are a little higher than those found in Grometry 17 and this may be due to the influence of the taller leeward buildings. The presence of the buildingschanges completely, the pressure patterns on the roof of the mall. As expected high positive pressures were recorded to the windward and high negative values were found between the buildings. This latter area shows different contour patterns as the pressure distribution is influenced directly by the height of the leeward building. The smaller plan area to the leeward of all the buildings is the negative pressure area in both cases.

315^{o} Wind (Figs. 59, 62 and 66)/

315^{o} Wind (Figs. 59, 62 and 66)

Windward Sides

Although the pressure patterns for both the long and short sides are similar the values recorded for each geometry are different. The long sides in Fig. 62 and 66 show an additional small negative pressure area. This is caused by the air flowing round the base of the windward building.

Leeward Sides

A negative pressure regime is maintained for Geometries 16 and 17. and the measured pressures have high negative values, the pressure pattern being different to that found in Geometry 15 and this is due, obviously, to the presence buildings.

Plan

The pressure patterns and pressure coefficient values are similar for Geometries 16 and 17 on the windward area and that area between the buildings. In the latter area the contour pattern is different as the higher leeward building in Geometry 16 is reducing the negative pressure coefficient values as all buildings produce a positive pressure area to their windward. The negative pressure values on the leeward area of the roof show a corresponding difference between Fig. 62 and Fig. 66.

225^{o} Wind (Figs. 59, 63 and 67)/

225° Wind (Figs. 59, 63 and 67)

In general the overall pressure patterns in Fig. 63 are similar to those found in Fig. 62.

Windward Sides

The pressure pattern for all three geometries is similar but the values increase with the height of the windward building. On the long side the additional negative pressure area found in Geometry 16 is again due to the air flowing round the base of the near building. High negative pressure values were observed at the leeward end of the side in each case.

Leeward Sides

Both leeward sides in Figs. 63 and 67 show small variations only but the short sides have areas of very high negative values at their windward ends.

Plan

The leeward part of the roof shows similar pressure patterns and pressure values for Geometries 16 and 17. The pressure patterns for the windward sides are similar but the pressure coefficient values in Fig. 63 are higher than the corresponding values in Geometry 17. The pressure regime between the buildings is markedly different. The positive pressure area in/

in Fig. 67 is allowed to form because of the small influence, relatively, of the two unit high building. For Geometry 16 the taller windward building creates a large area of negative pressure which does not allow the positive pressure pattern to develop.

180° Wind (Figs. 58, 64 and 68)

Windward Sides

The absence of the negative pressure area in Fig. 68 suggests that the creation of these low pressure areas are dependent on building height. Higher positive pressure values are recorded for Geometry 16 than those recorded for corresponding points in Geometry 17.

Sides Parallel to the Wind

Comparing Geometry 15 and 17, it is found that the positive pressure area is shifted to the windward end of the side but in Geometry 16 this area does not appear, due to the greater effect of the taller windward building.

The pressure coefficient values found in Figs. 64 and 68 are similar in that the tall building to the windward creates high negative values, whereas the small building has no pronounced effect but the air flow deflected by the large building in Geometry 17 produces the high negative values similar to those near the foot of the windward building in Geometry 16.

Leeward Sides/

Leeward Sides

Figs. 58, 64 and 68 show a progressive increase in the negative pressure coefficient values for these sides. The higher values found in Geometry 17 are caused because the near building has a greater influence on the air flow than its companion building in the same Geometry.

Plan

The area to the leeward of the buildings shows a fairly constant pattern in Geometries 16 and 17, the higher values in Fig. 68 being created by the same cause as that found to explain the difference in pressure coefficient values on the leeward sides.

The windward areas have positive pressure patterns, the higher values in Geometry 16 being due directly to the increased height of the adjacent building.

In between the buildings the pattern in Fig. 64 is similar to that found in Fig. 61 as the geometrical relationships are similar for these cases. For Geometry 17 the high positive values and the steep pressure gradient are both caused by the down flow of air generating a strong axial vortex.

10. Comparison of Geometries 15 and 18 (Figs. 58,to 60 and 69 to 73, inclusive).

These geometries are similar basic malls (i.e. without buildings of plan propotion 7·5 to 10. Geometry 18 has a courtyard which/

which is placed asymmetrically with respect to the minor axis. A comparison of the two theories of results shows that the courtyard creates local disturbances of a low order only both to the pressure patterns and the pressure coefficient values which have been recorded on the mall surface.

11. <u>Comparison of Geometries 19 and 8</u>
<u>(Figs. 24 - 28 and 74 - 78, inclusive)</u>

In general there are many similarities between these two geometries and the effect of the courtyard on the mall roof pressure pattern is very local. The pressure patterns and coefficient values for the sides are all similar for each wind direction.Although the influence of the larger longer building in Geometry 19 can be observed, the pressure regimes on the mall roof surface are similar both in shape and pressure coefficient values.

12. <u>Comparison of Geometries 18 and 19</u>
<u>(Figs. 69 to 73 and 74 to 78, inclusive)</u>

This section deals in particular with the pressure regimes found in the courtyard.

Considering Figs. 69b, 71b and 73b (Geometry 18) the pressure pattern and the measured values are similar. This is to be expected as the flow of air in and around the courtyard will follow similar paths and no buildings are present on the mall surface to disturb the air flow. In addition, the results shown in Fig. 75b (Geometry 19) are similar to those in the courtyards where no associated buildings exist as the air flow is little disturbed in this case. Equally, Figs 70b and 72b

(Geometry/

(Geometry 18) show some similarity.

Comparing Geometries 18 and 19 for the 180^{o} wind (Figs. 73b and 77b) it is seen that a pressure pattern in the courtyard is similar although the values for Geometry 19 are increased.

Throughout these Geometries (18 and 19), it may be observed that the similar pressure patterns in the courtyards occur when the courtyard is to the windward of the building.

The courtyards in the lee of the buildings for Geometry 19 (Fig. 74b and 78b) exhibit different pressure patterns when compared with the corresponding results for Geometry 18 (Figs. 69b and 70b). Considering these results for the zero degree wind (Figs. 69b and 74b) the positive pressure regime in Geometry 18 is transformed to a negative pressure area with relatively high values. Considering Fig. 70b and 78b, an area of negative pressure is induced in the courtyard due to the building, and the pressure coefficient values are relatively high.

RESULTS OF THE AIR-FLOW OBSERVATIONS

These results are presented diagrammatically in Figures 101 to 181 inclusive. Figures 101 to 178 relate directly to the geometries and air-flow directions in the pressure contour diagrams, i.e. Figures 1 to 78. Figures 179 to 181 are an attempt to measure the flow velocity at various points over the mall and buildings for Geometry 14.

The lines of air flow are, in each case, those lines of air movement which appeared most prominent using the only suitable visualisation technique available at the time of observations, which was a single jet of paraffin smoke. The jet was moved round the model and the main disturbances in air movement were sketched on a simple diagram of the particular geometry. The sketches were then transferred into the isometric views presented here. General trends in the flow patterns can be seen for those geometries that have some similarity of layout.

In the discussion of these results little mention has been made of any flow/pressure relationship. This is due to the fact that the pressure changes on the surfaces of the malls are, in many cases, a function of a volume flow over various parts of a building geometry. This applies in those cases where a steep pressure gradient over part of the mall surface was measured. The flow at the same location may appear simple/

simple in the diagrams, as the influence of the movement (in terms of both direction and speed) of air in the volume between the point(s) of pressure measurement and the undisturbed air stream has not been quantified.

The flow patterns may serve as a guide to the possible smoke movement outside the buildings. For example (Figures 28 and 128) any smoke being drawn out of the mall roof could circulate over the leeward face of the tower block. This smoke could penetrate into the block as positive pressures have been recorded on the edges of the leeward side of the block.

The discussion which follows is presented in three major sections. The first (Section A) discusses the development of flow patterns with the wind flowing parallel to the longitudinal axes of the malls. The second (Section B) deals with all geometries but with the wind flow at an angle of 45° (135°, 225° and 315°) to the longitudinal axis of the mall and the third (Section C) discusses the flow patterns generated with the air flow parallel to the minor axes of the malls (i.e. wind angles 90° and 270°). In each of these sections similar geometries are grouped for the purposes of discussion. The fourth section (Section D) is a comment on the velocities measured for Geometry 14.

SECTION A. DEVELOPMENT OF FLOW PATTERNS - WIND PARALLEL TO LONGITUDINAL AXES

Discussion

(1) Geometries 1, 3, 15 (Figs. 101, 107 and 158)

These patterns are similar, the edge effects are most marked in Fig. 101. In general the flow is reasonably uniform over the mall shapes and the flow from the top along the sides gives rise to pressure variations, as without this flow the zero contours could be expected to be vertical. (Figs. 1, 7 and 8).

The flow behaviour over the windward and leeward sides is common to these geometries and can be observed in many other geometries.

(2) Geometries 2, 4, 5, 6, 7, 8, 9. (Figs. 104, 110 113, 116, 123, 128 and 133).

In these geometries a main feature of interest is the development of the upward movement of the air stream round the sides of the building and into the leeward air volume. As the building size increases, the value of the negative pressures increase behind the sides,to the leeward, of the building. This is due to the greater disturbance of the main air stream which generates larger volumes of low pressure on the leeward side. This effect becomes more marked in Geometries 7 and 8 and exists also in Geometry 9.

Referring/

Referring to Figs. 110, 113 and 116, and taking Geometry 4 as a base, the negative pressures developed in Geometry 5 are greater, due to the air stream adjacent to the side of the building having a greater apparent velocity, i.e. the main air stream is less disturbed, therefore the mass flow rate around the building is greater than that in Geometry 4, so the pressures will be more negative. It is shown also that less spillage of air takes place over the edges of the mall and this is confirmed by the pressures recorded on the long sides of the mall.

For Geometry 6 the flow is less disturbed because of the small size of the building.

On the windward sides of all these Geometries (NB for Geometry 7, Fig. 119; Geometry 8, Fig. 124; Geometry 9, Fig. 129) there can be seen a progressive development of vortex motion which results in higher positive pressures as the buildings increase in size.

(3) <u>Geometries 16 and 17 (Figs. 161, 164, 165 and 168)</u>. Considering the flow on the windward side of Geometry 16 (Fig. 161) it may be seen that some air is drawn into the space between the buildings. This space contains large scale eddies. Another feature, noted on many other geometries, is the reverse flow, on the windward side of the buildings, which/

which extends to about the height of the buildings at ground level.

Fig. 165 (Geometry 17) shows that the windward patterns are similar to those in Geometry 16. However, the major point of interest is the slow, indecisive amount of air between the buildings and the generation of a large scale circulation above the space, which is fed by air flowing back from the leeward side of the buildings. The flows indicated in Fig. 168 show the common distribution over the taller building but the flow over the smaller building is reversed, making the pressures in its wake positive.

(4) Geometries 18 and 19 (Figs. 169, 173, 174 and 177)
The flow over the mall is similar to that observed in Geometry 15, but the courtyard creates a local disturbance. The pattern of flow in the courtyard suggests that the air is drawn out of the space at the windward side with replacement air flowing down at the leeward side. This basic flow pattern is retained when the building is added in Geometry 19, although the flows observed for Geometry 8 (Figs. 128 and 124) are superimposed.

(5) Geometries 14 and 4 (Figs. 155 and 110
The general features of the flow are somewhat similar for these Geometries but the presence of the slot allows air to flow under the windward face of the building. This has the effect of reversing the rotation of the flow on the leeward side of the building.

(6)/

(6) Geometries 10 and 11 (Figs. 134, 138, 139 and 143)

Considering Figs. 134 and 139, the flow distribution over the main block is similar to the flows observed in many of the configurations. The small block in Geometry 11 produces little disturbance to the flow pattern. This is supported by a comparison of the pressure contours in Figs. 13 and 39. Although Geometry 10 is the more complex, the distribution of air over the "secondary" buildings follows the common pattern.

Figs. 138 and 143 show the flow patterns in the opposite wind direction. The common pattern of distribution is observed in Geometry 10, but the small building in Geometry 11 causes a significant and advantageous change in the pressure patterns (Figs. 13 and 43) by causing a greater flow between the two buildings.

SECTION B. DEVELOPMENT OF FLOW PATTERNS.
WIND PARALLEL TO MINOR AXES.

(1) Geometries 1, 3, 15. (Figs. 103, 109 & 160)

The flows over these geometries exhibit the same features as noted in Section A above.

(2) Geometries 2, 4, 5, 6, 7, 8 and 9
(Figs. 106, 112, 115, 118, 121, 126 and 131)

The flows observed for these geometries are all similar and it can be seen that the flows over the mall are much less disturbed than for the longitudinal cases. The presence of the building appears to accelerate the air which flows along the base of the building, thereby bringing the negative pressure contours nearer to the windward edge.

(3) Geometries 12 and 13. (Figs. 148, 150, 152 and 154)

Considering Figs. 150 and 154 the flow over the mall is disturbed in the proximity of the building only. The flow over and round the buildings is similar to the flows observed in other geometries when the broader face of the building is exposed to the wind.

In Figs. 148 and 152 the common air flow distribution is again observed on the windward face of the buildings. Geometry 12 has a greater effect on the flow over the mall than does Geometry 13 and this is confirmed by the change in pressure patterns (Figs. 48 and 52).

(4)/

(4) Geometries 10 and 11 (Figs. 136, 141 and 145)

In general the flows over the buildings are similar to those observed on single buildings. It is interesting to note that the down flow, on the windward side of the bulkier building which is set back from the edge of the mall in Geometry 10, is turned back into the main flow over the edge of the mall. This is a feature found to be common in buildings of these or greater proportions. From these diagrams the modification of the flow over the mall alone (compared with Geometry 3) can be observed clearly.

(5) Geometries 4 and 14 (Figs. 112 and 157)

The flow patterns are similar but the presence of the slot in Geometry 14 modifies the air flow on the windward side so that the pressures on the mall side are reduced. Apart from this, there is little difference in these geometries.

(6) Geometries 18 and 19 (Figs. 171 and 175)

The addition of the building makes little difference to either the flow or pressure patterns. The flow around the building is similar to that in the other geometries (e.g. Geometry 8) where a flush mall/building face is presented wo the wind.

SECTION C. DEVELOPMENT OF FLOW PATTERNS
WIND AT 45° TO MAJOR AND MINOR AXES OF MALLS.

(1) Geometries 1, 3 and 15 (Figs. 102, 108 and 159)

From the observations made, the size of mall appears to have no effect on the airflow over the shape. The direction of the main airflow is unchanged over these shapes.

(2) Geometries 2, 4, 5, 6, 7, 8 and 9. (Figs. 105, 111 114, 117, 120, 122, 125, 127, 130 and 132

When the airflow is over the mall, it is little disturbed except in proximity to the buildings and the degree of disturbance is related to the building height. The change in the corresponding pressure patterns tends to confirm that the disturbance is some function of building height.

With the airflow over the building, there is a general tendency for a reverse flow to occur near the windward end of the building. This reverse flow is more marked in some geometries than others and may be a function of building height also. This is confirmed by an examination of the corresponding pressure contours.

(3) Geometries 12 and 13 (Figs. 147, 149, 151 and 153)

Considering Figs. 147 and 151, the disturbance of flow over the mall is influenced by the nearness of the building. Comparing/

Comparing Figs. 149 and 153, the flow over the mall is influenced by the closeness of the building. A feature of interest is the upward flow from the mall in Geometry 12 and the increased negative pressures measured in this area (Fig. 49).

(4) Geometries 10 and 11 (Figs. 135, 137, 140, 142, 144 and 146).

The flows observed in these diagrams combine many of the features seen in the axial and the 45° flows for other geometries.

In the flow over the mall, some air flows in relatively undisturbed lines. Where the flow is able to flow between the closely spaced buildings, an apparent high flow rate is generated which may give rise to the large pressure changes at these locations.

(5) Geometries 4 and 14 (Figs. 111 and 156)

The flows over these geometries are similar, as expected, but the presence of the slot creates a strong flow over the lee side of the mall and the air movement pattern on the leeside of the building appears to be more definite. In Geometry 4 there is a clearly observed flow around the lee edge of the building, whereas the slot in Geometry 14 eliminates this feature, or it allows a strong flow over the mall surface.

(6)/

(6) Geometries 8, 18 and 19
(Figs. 125, 127, 170, 172, 176 and 178)

The flows for Geometry 19 are clearly marked. The flow in the courtyards for Geometries 18 and 19 are similar. A comparison of Geometries 8 and 19 shows many similarities in flow pattern. Again the flows over those parts of the mall away from the building are little altered from those observed in G ometry 18 (and 15) and the courtyard has little effect on these flow patterns.

SECTION D. AIR VELOCITY MEASUREMENT

Geometry 14 (Figs. 179, 180 and 181)

This comment is confined to the flow at the top surface of the mall. The coefficients presented are related to the flow speed on the velocity profile (Fig. A 1) at the height of the mall (i.e. 50mm) in the wind tunnel.

(a) Flow along major axis

The flow over the windward edge is unaffected initially. Nearer the building the velocity is increased, due to air flowing down the building and a flow coefficient of 2·34 was measured under the building, more than twice the reference velocity. The air deflected round the building has an increased velocity (Cv between 1·6 and 2·1) which is due to the air flowing round the windward side of the building. A high velocity is maintained on the leeward side for some distance until the reverse flow regime is established.

(b) Flow along minor axis

The flow over the mall is accelerated to 1·6 times the reference velocity. The flow under the building is little different and these small variations may be regarded as similar to the pressure changes presented in Figs. 9 and 57.

(c)/

(c) Flow at 45^o to mall axes

Again there is little change in the velocity over the windward surface of the mall, but some acceleration takes place near the building giving a maximum Cv of about 2. Over the leeward side of the mall surface there is a reasonably constant velocity (Cv about 1·8) leaving the slot, but the velocities further from the building show a decrease in velocity. The corresponding pressure pattern (Fig. 56) shows a change in values which may be comparable to the variations in velocity.

CONCLUDING REMARKS

1. From the results of this investigation, it is clear that many of the building geometries tested would generate adverse pressures on the surfaces of the malls. The values of these pressures can be obtained readily by multiplying the pressure coefficient (as presented) by the dynamic pressure generated by a selected free wind speed. The actual predicted pressure must then be evaluated by a comparison with the pressures within the mall generated by the stack effect (due to differential ambient temperatures) and by a possible fire.

2. It is suggested that the pressure patterns for building geometries similar to those examined could be interpolated. Also, it may be possible to extrapolate values for some geometries as the change in pressure pattern with building geometry is quite marked. However, use of the pressure probe developed during this investigation should enable any model, of a suitable size, of a proposed town centre complex to be assessed for vent operation.

3. As so many of the geometries give positive pressure areas on the mall roof, there may be some virtue in developing a pressure sensitive device for use with automatic vents. This could be an electrical resistance strain gauge mounted on a thin metal diaphragm monitored through the circuits used by any installed fire detectors. Such a device would stop a vent opening under adverse pressure conditions.

(BLANK PAGE)

DEVELOPMENT OF PRESSURE AND FLOW PATTERNS
ON SHOPPING MALLS DUE TO NATURAL WIND.

APPENDIX A

EXPERIMENTAL TECHNIQUE

1. WIND TUNNEL

The general arrangement of the tunnel, model and measuring equipment is shown in Plate 1. The tunnel is an open jet low velocity tunnel which has been used for studying urban wind problems for about 15 years and the conditions in the measuring area of the tunnel show a good correlation to the actual wind conditions in urban areas.[1]

2. WIND

The wind tunnel has been arranged to produce a turbulent wind which has a vertical velocity profile equivalent to that which exists in urban areas (see Figure A.1). The turbulence spectrum corresponds to that suggested by Davenport[2] for high wind conditions.

3. PRESSURE PROBE

Because of the large number of measurement points and the relative insensitivity of liquid manometers (U-tube type) the idea of a pressure probe was examined. The original probe (perspex "button" (Figure A. 2(a)) gave pressure readings comparable to conventional pressure tappings at angles of 0^{o} and 90^{o} to the air flow. Discrepancies occurred at intermediate/

intermediate angles due to the geometry of the probe.
The probe was modified (Figure A.2(b)) so that a "feather edge" was presented to the air flow on the side of a model. This modification allowed measurements to be taken with the probe on a surface at any angle to the air flow. Figure A.3 is a graph which compares the performance of the probe with a conventional pressure tapping from a hole on the surface of a model. Because of the asymmetry of the probe, check readings were made with the line of the outlet tube horizontal (i.e. parallel to the air flow) and the outlet tube vertical (i.e. at right angles to air flow). From the measurements, it was concluded that the modified probe was sufficiently accurate and could be adopted for pressure measurements on the mall models.

4. THE MEASURING SYSTEM

The outlet from the probe is connected to a micromanometer, calibrated directly in N/m^2. A centre zero scale enables positive and negative pressures to be identified easily. A pressure balance tube is connected to the outlet of the manometer and led to a hole in the wind tunnel table so that the pressures recorded are the difference between the measuring point and the "basement" of the mall. This balance point is protected from all air flow.

The electrical output from the manometer is fed to a pen chart recorder, via an integrating circuit, so that a permanent record of/

of each measurement is made. The integrating circuit was found to be necessary as there were rapid fluctuations of the surface pressures due to the turbulent air flow. From the chart recorder the measurements were plotted on a gridded sketch of the model configuration under study. At the completion of each set of measurements all measurements were translated into pressure coefficients so that a direct comparison of different geometries was possible. This translation was found necessary because of the small, long term, variations in the flow generated by the wind tunnel.

REFERENCES

A.1 JONES, P M and C B WILSON (1968)
"Wind Flow in an Urban Area: A Comparison of Full Scale and Model Flows".
Building Science, Vol 3, pp 31-40.

A.2 DAVENPORT, A.G. (1961)
"The Spectrum of Horizontal Gustiness near the Ground in High Winds."
Qtly. Jnl. Royal Met. Soc. Vol. 87 pp 194-211

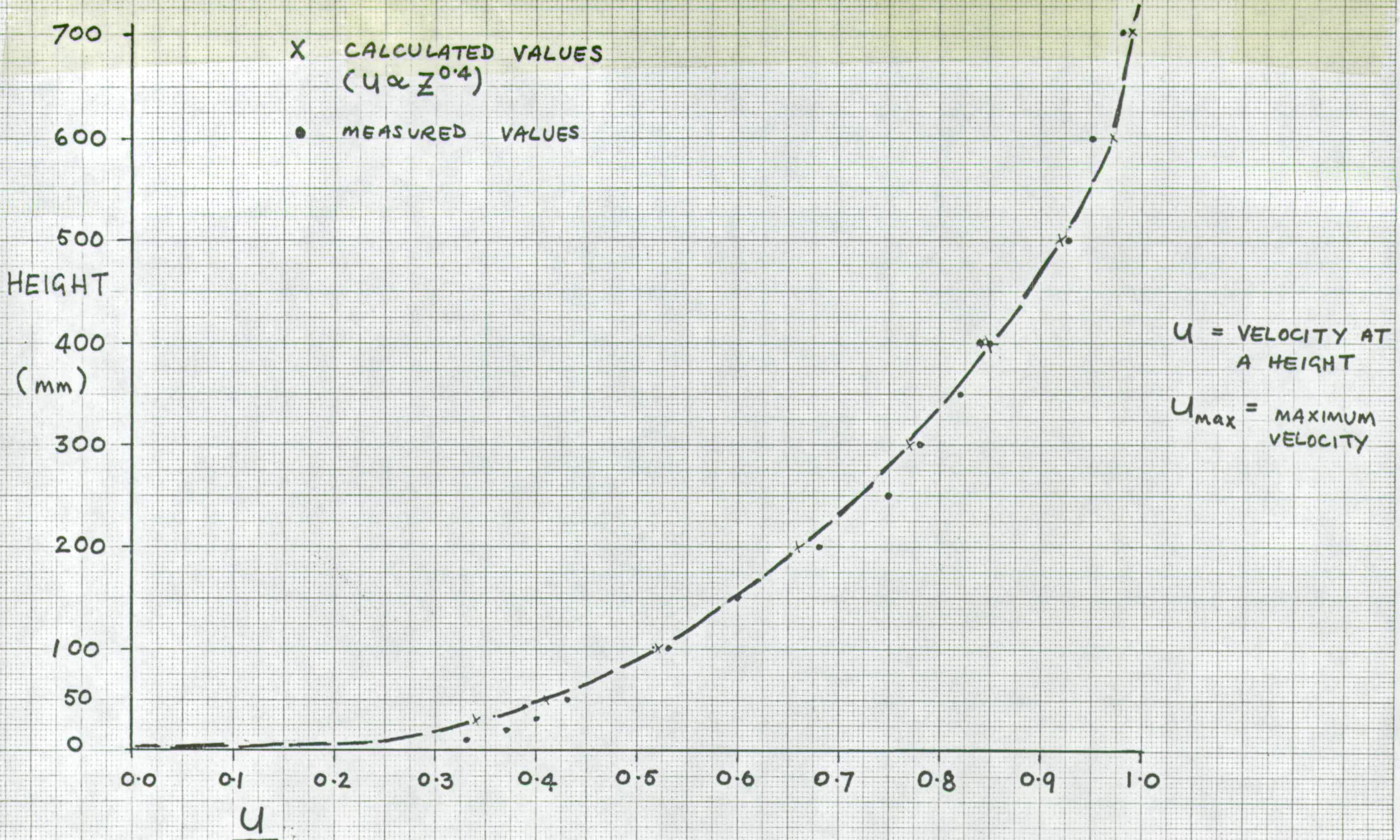


FIGURE A.1 VELOCITY PROFILE OF WIND FLOW

NB IN FIGURE (a) THE PROBE OUTLET WOULD BE PARALLEL TO AIR FLOW WHEN FIXED TO A VERTICAL SURFACE

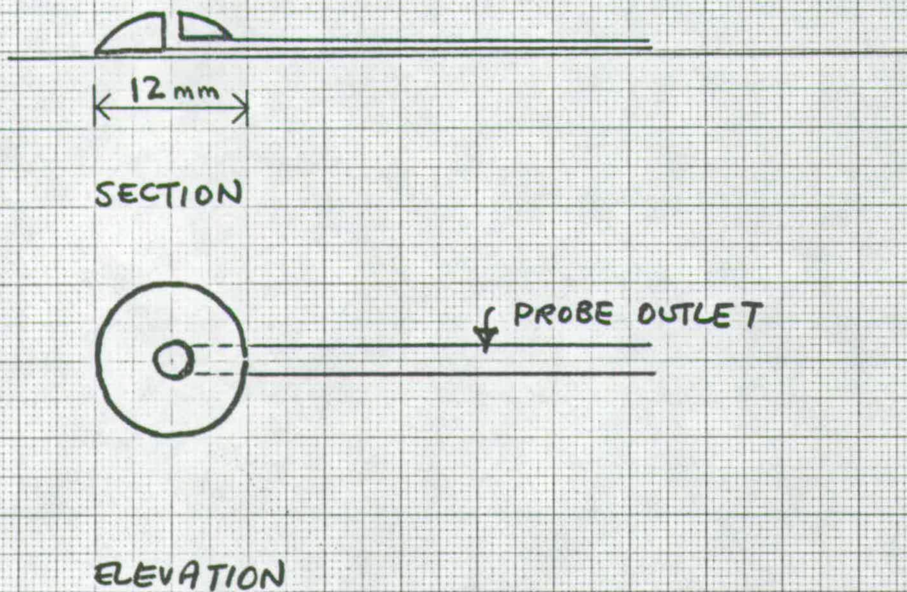
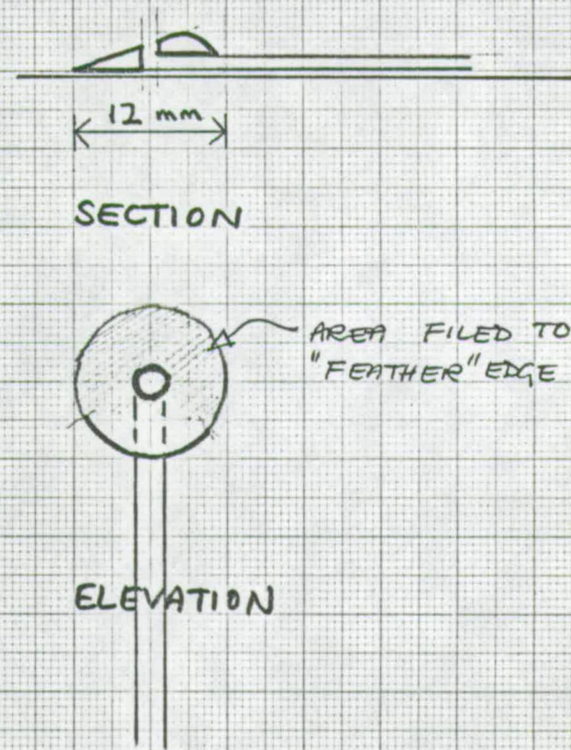


FIGURE A.2 (a)



PRESSURE PROBE DESIGN

FIGURE A.2 (b)

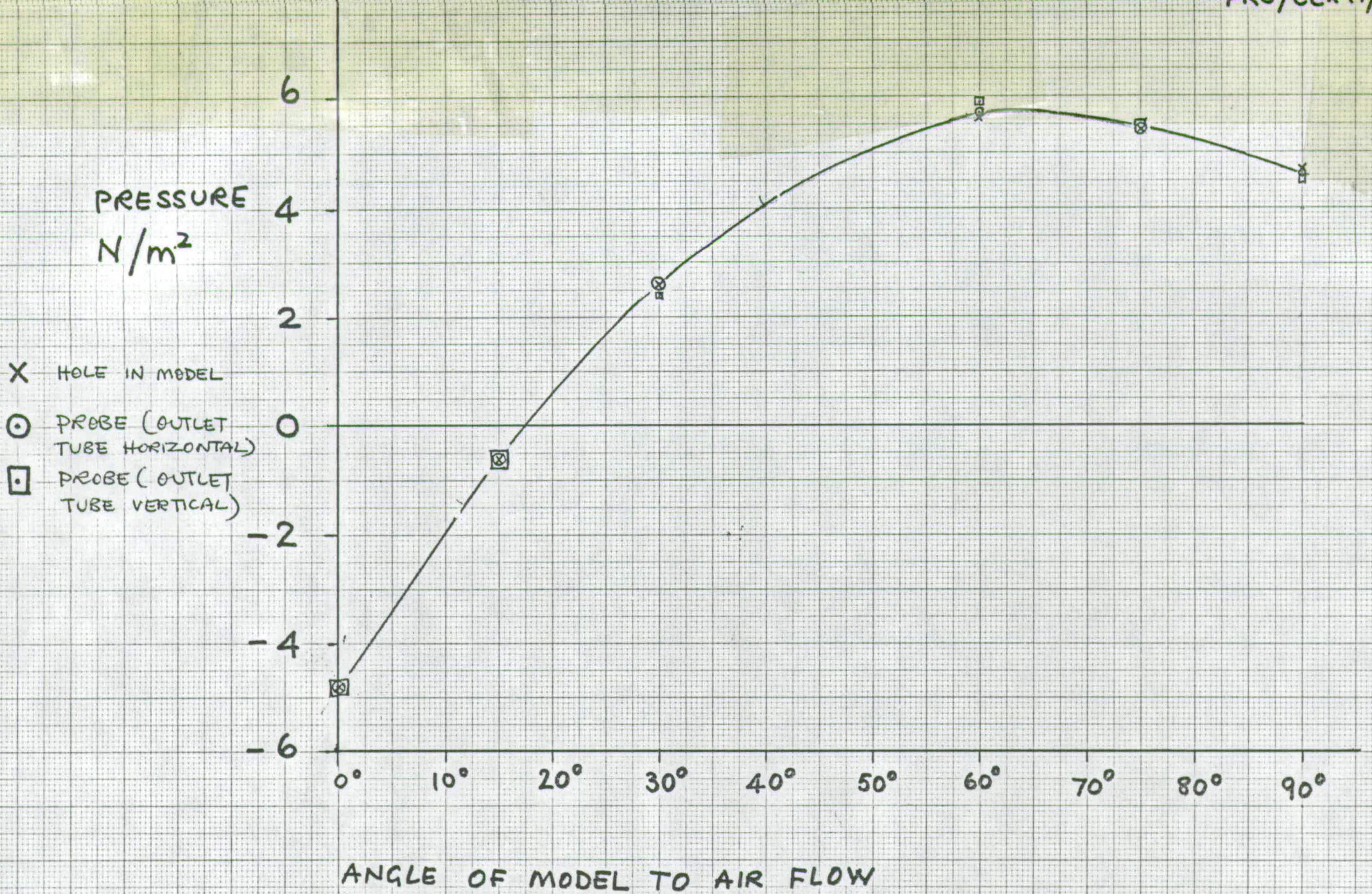


FIGURE: A.3 COMPARISON OF PRESSURE MEASUREMENTS

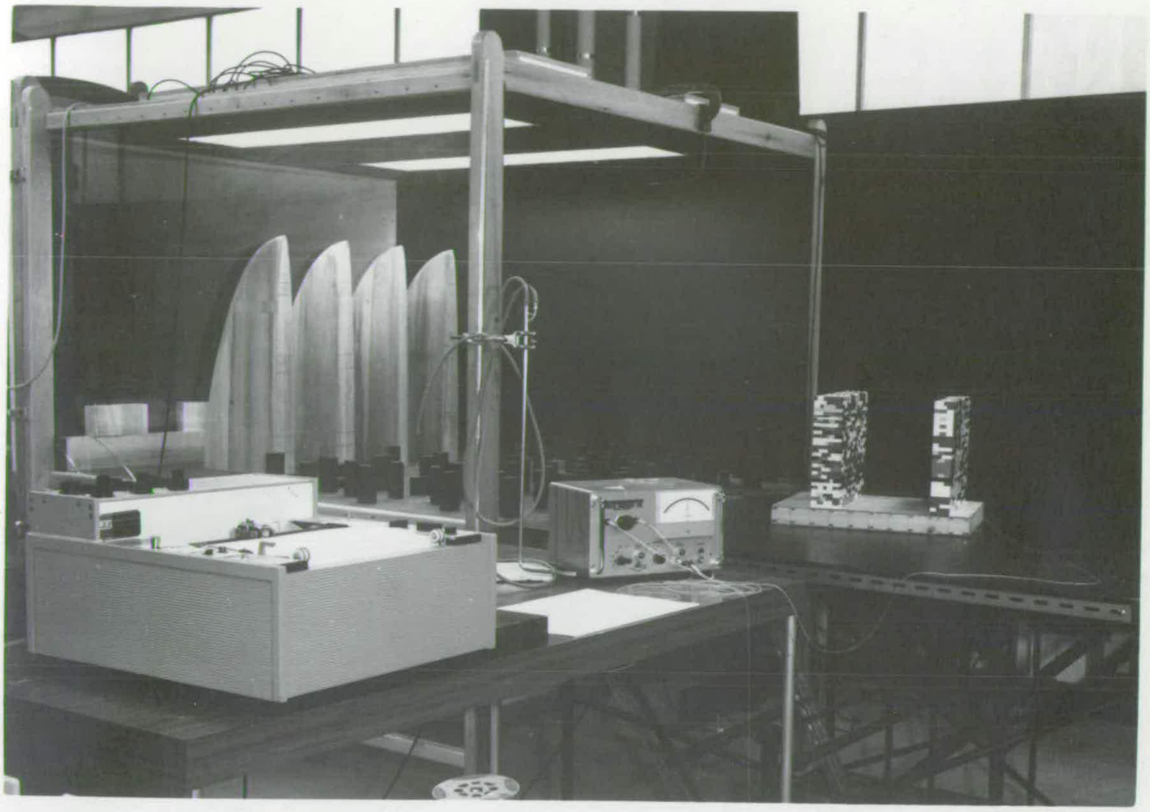
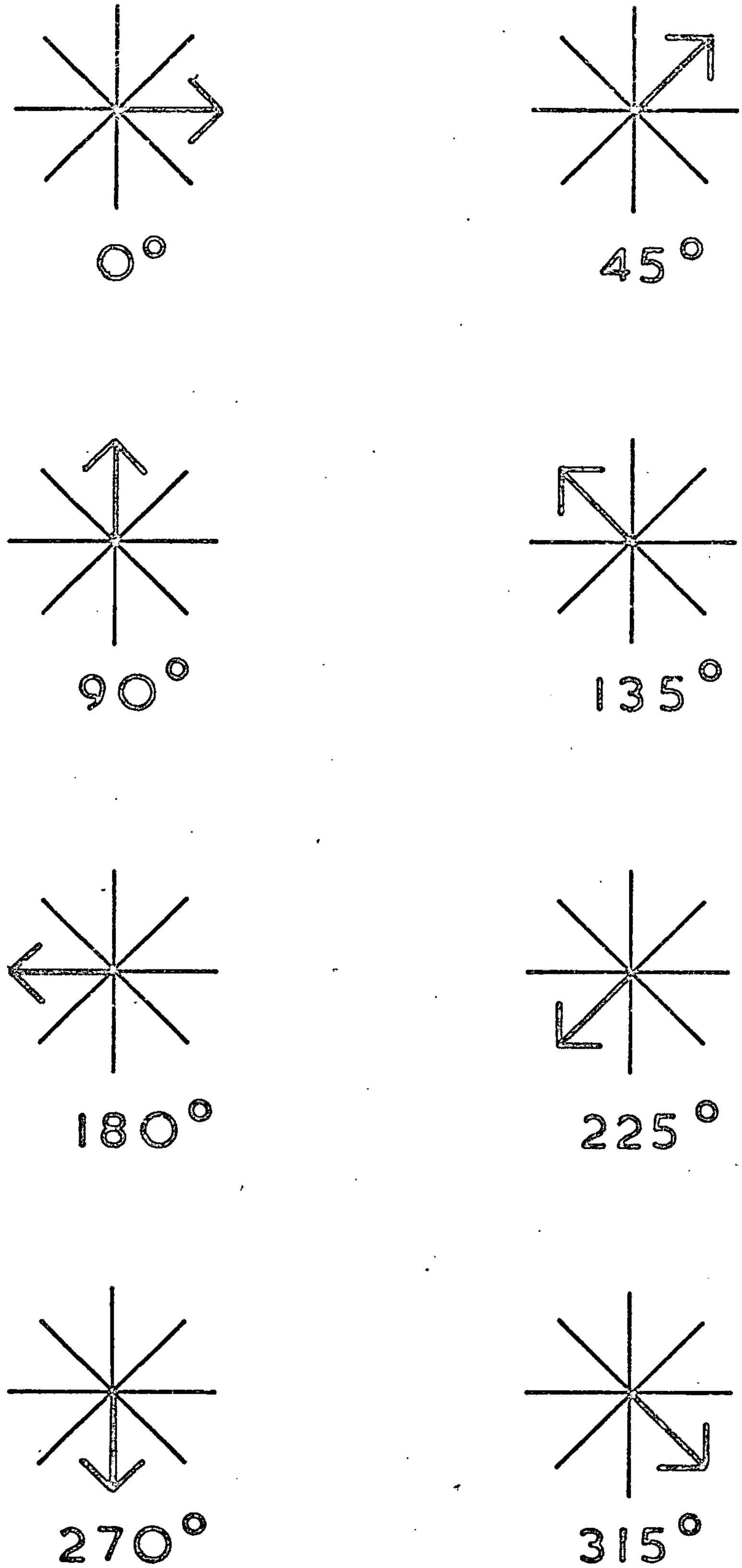


PLATE 1

General arrangement of Wind Tunnel, Model and Measuring Equipment.



KEY TO WIND DIRECTIONS

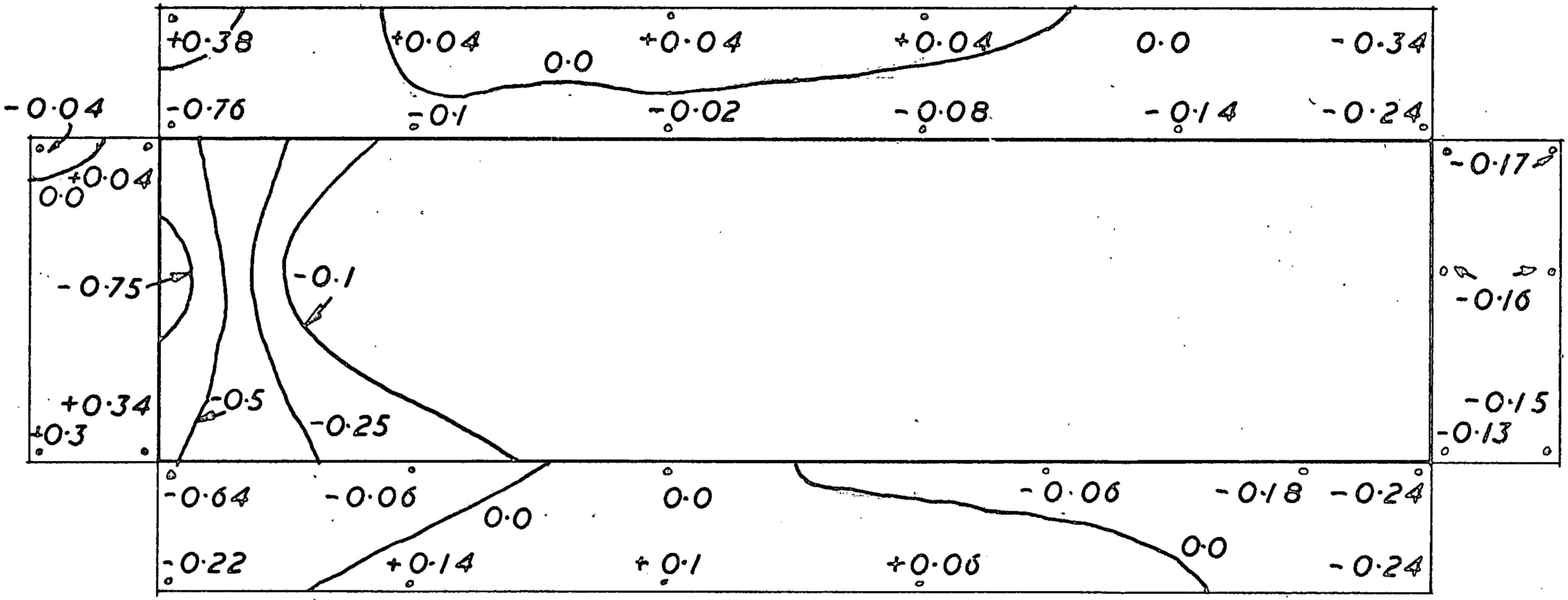


FIG 1 PRESSURE PATTERN GEOM 1 → WIND

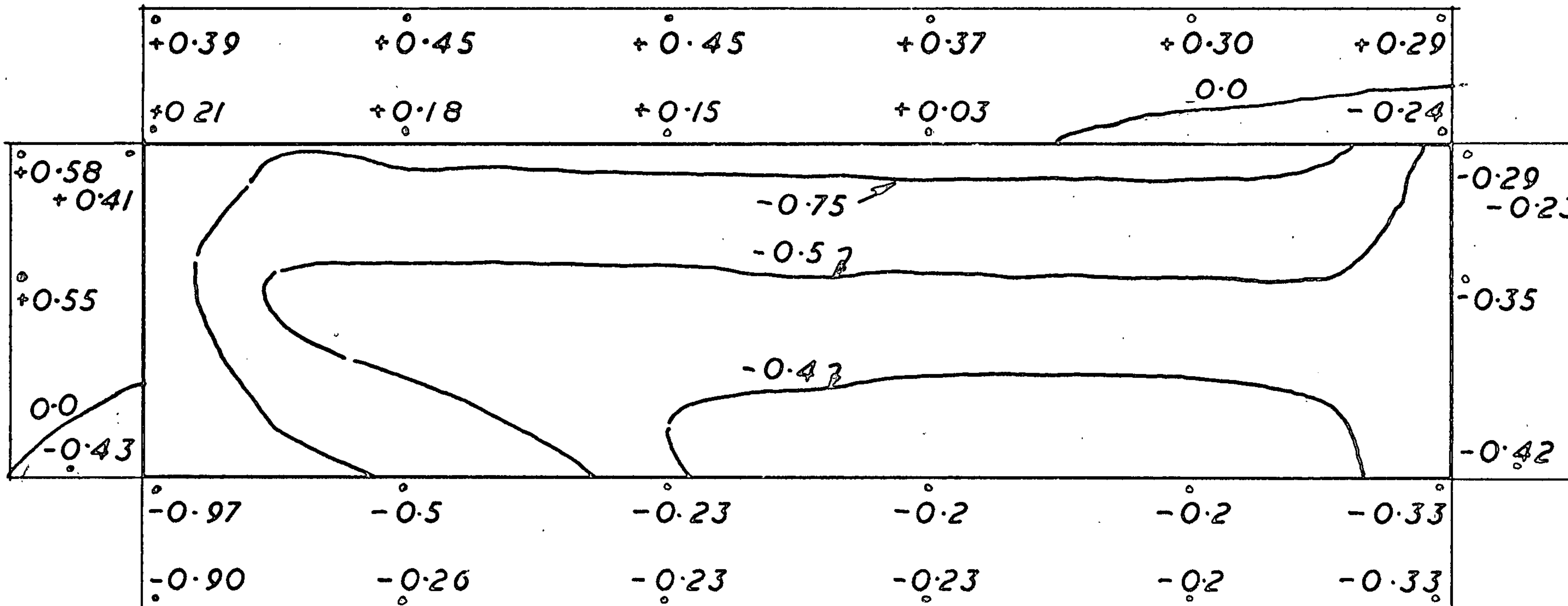


FIG 2 PRESSURE PATTERN GEOM I ↘ WIND

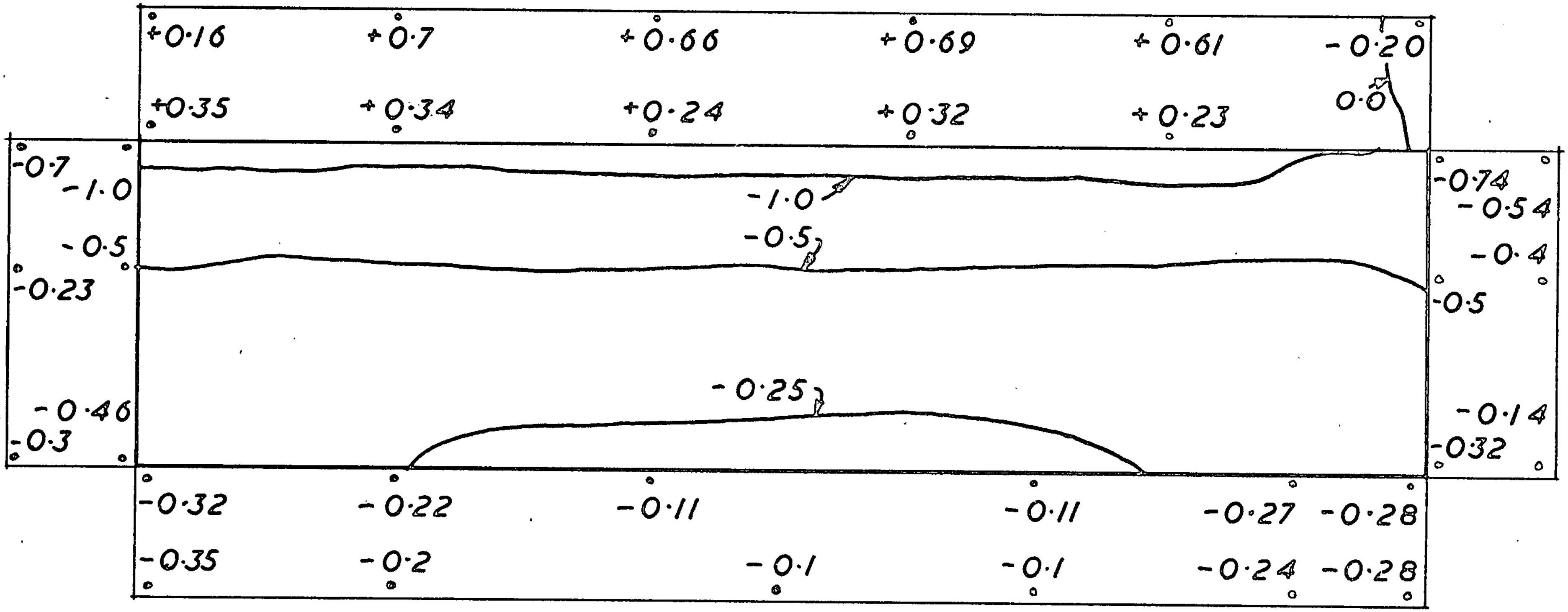


FIG 3 PRESSURE PATTERN GEOM I

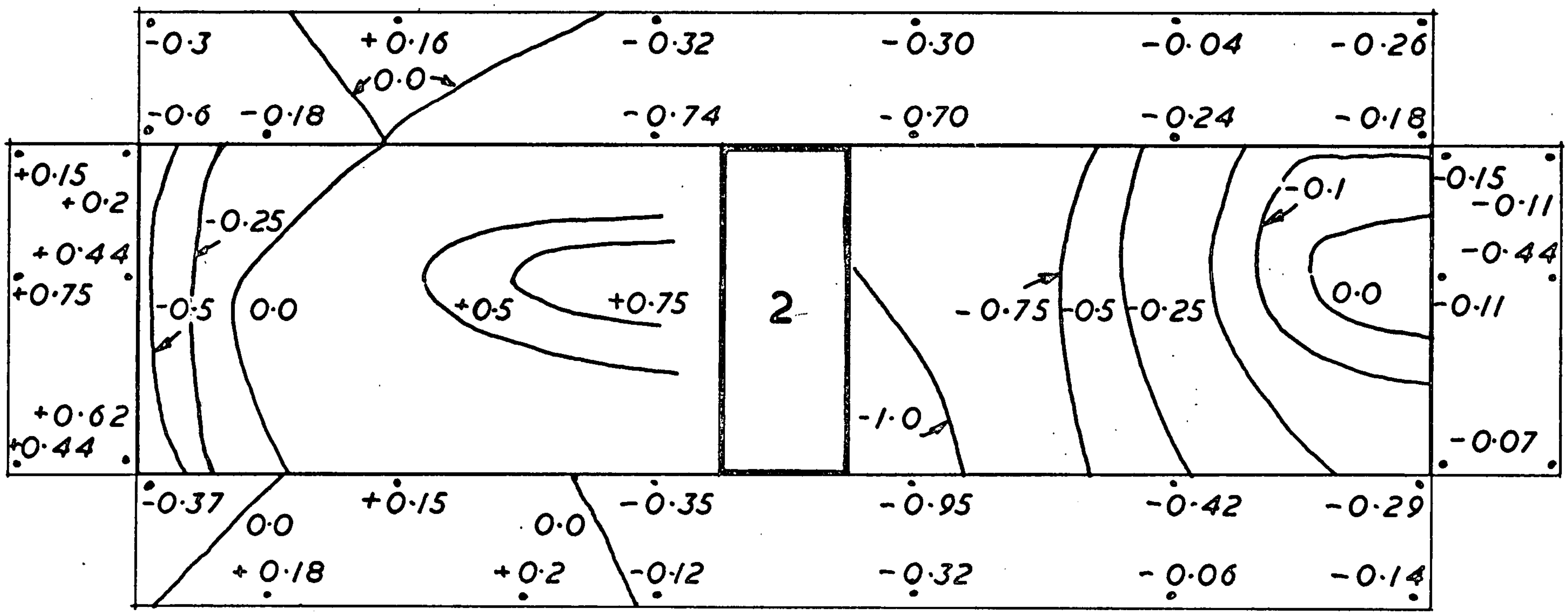


FIG 4 PRESSURE PATTERN GEOM 2 → WIND

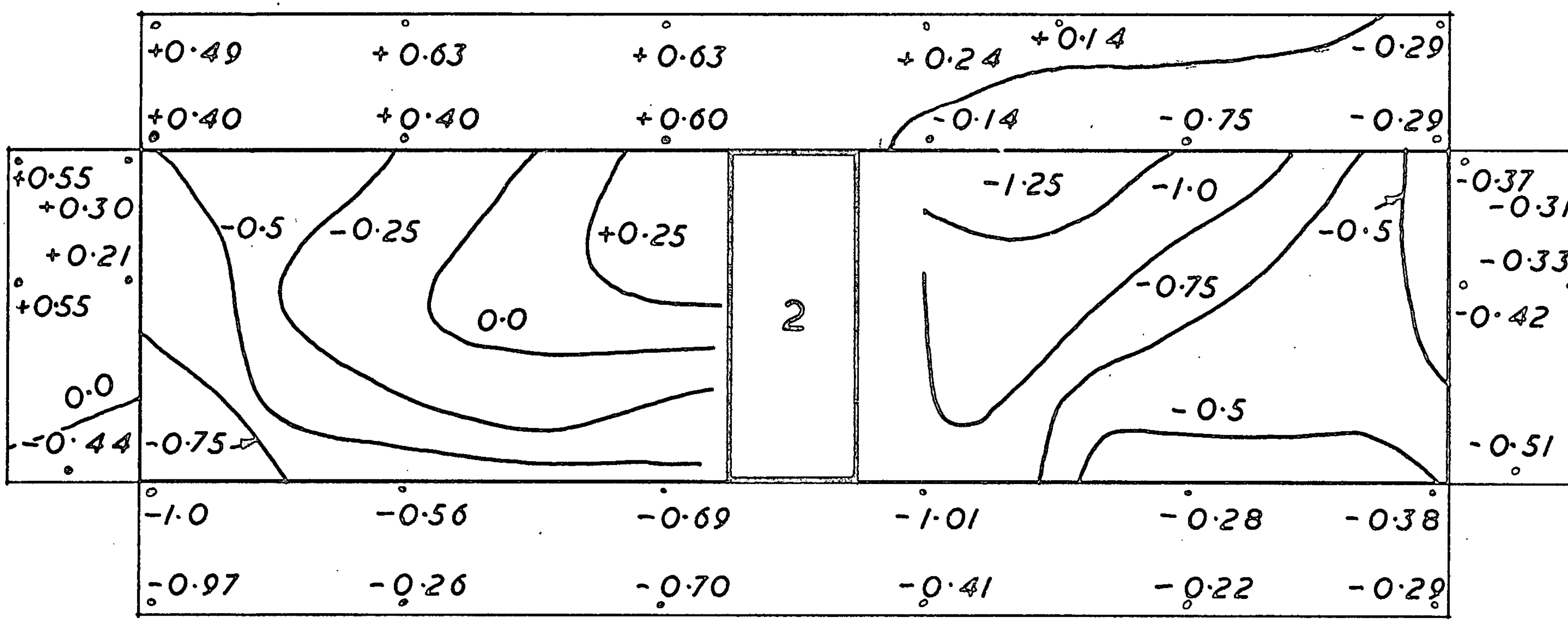


FIG 5 PRESSURE PATTERN GEOM 2 ↘ WIND

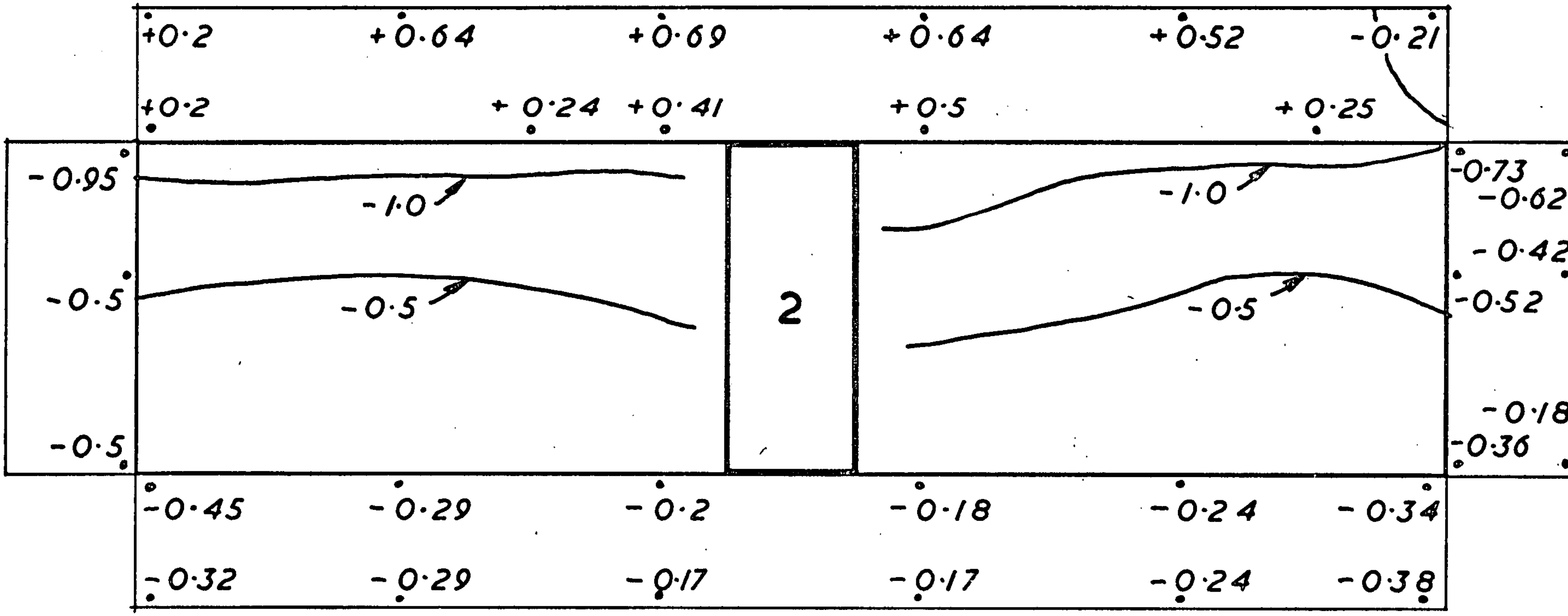


FIG 6 PRESSURE PATTERN GEOM 2 ↓ WIND

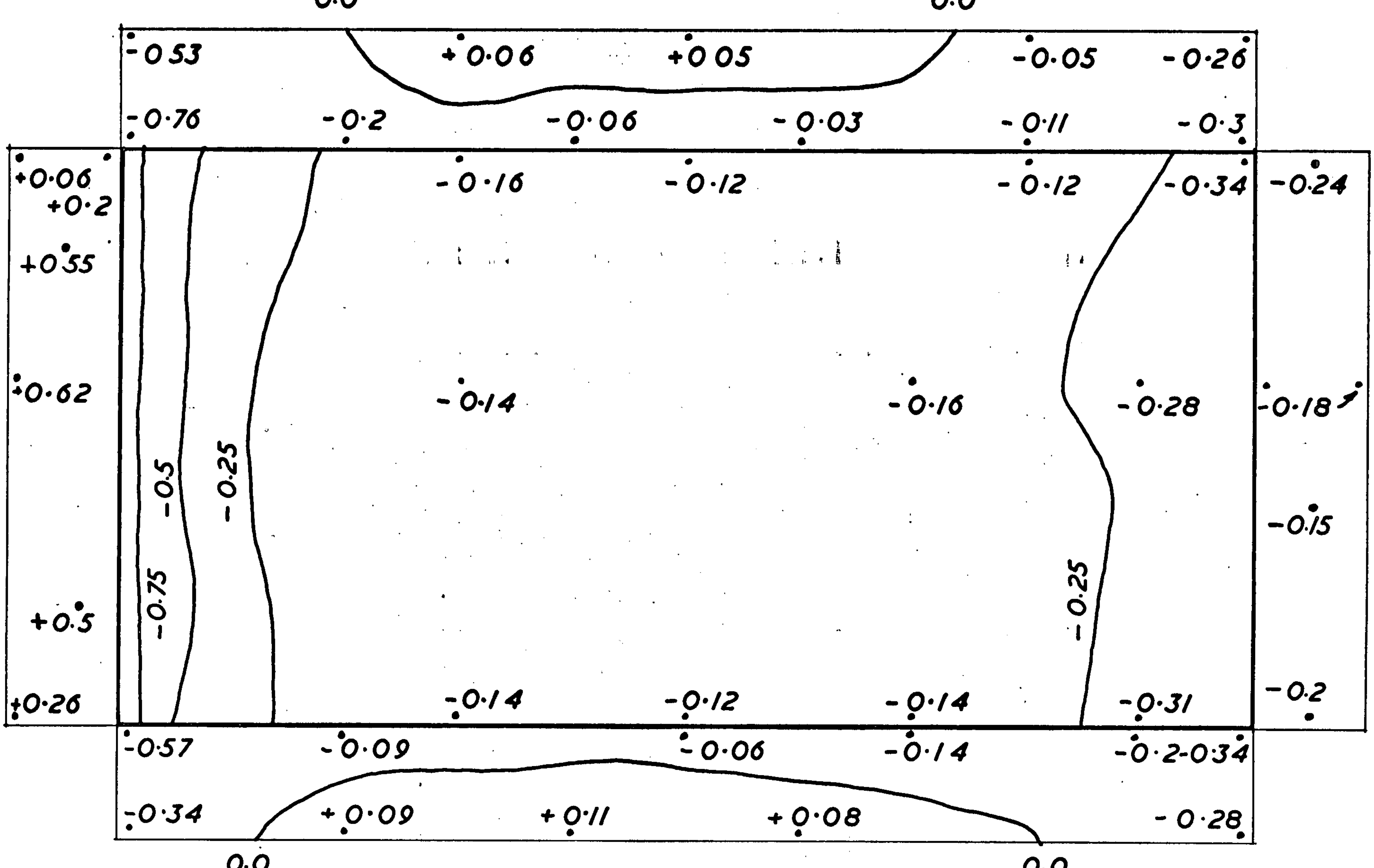
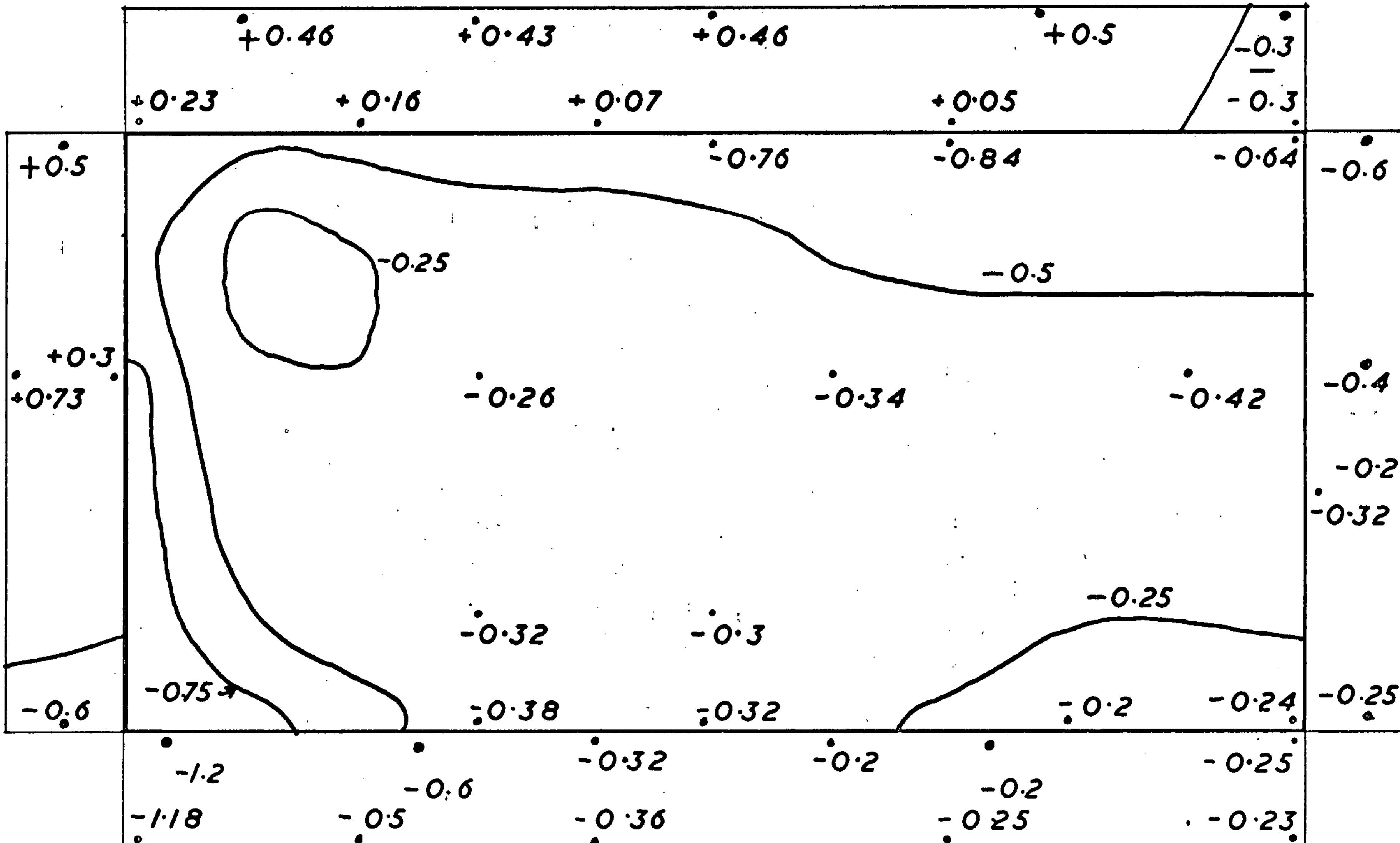


FIG 7 PRESSURE PATTERN GEOM 3 ⟶ WIN



PRESSURE PATTERN GEOM 3 ↘ WIND FIG 8

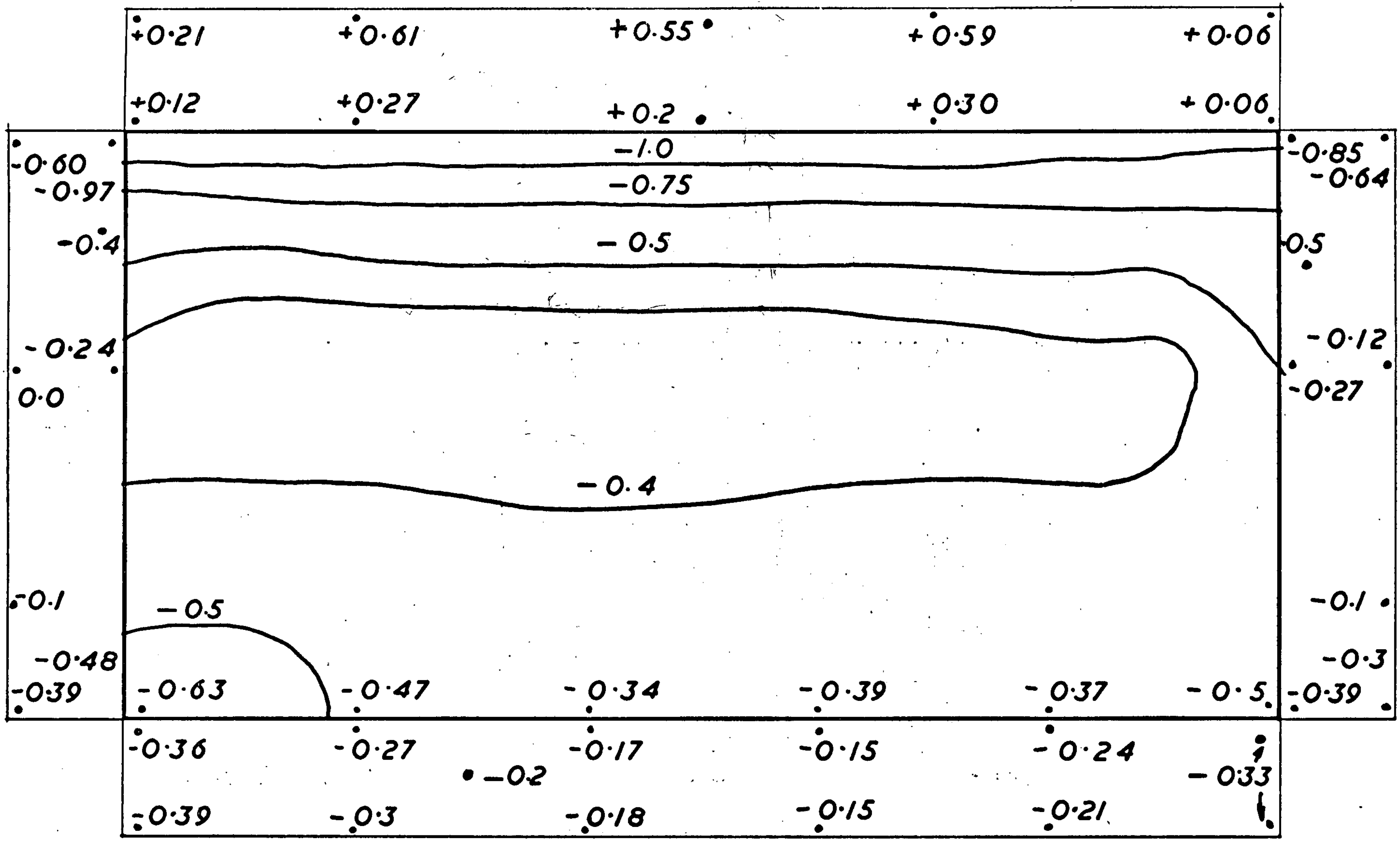


FIG 9 PRESSUREPATTERN GEOM 3 ↓ WIND

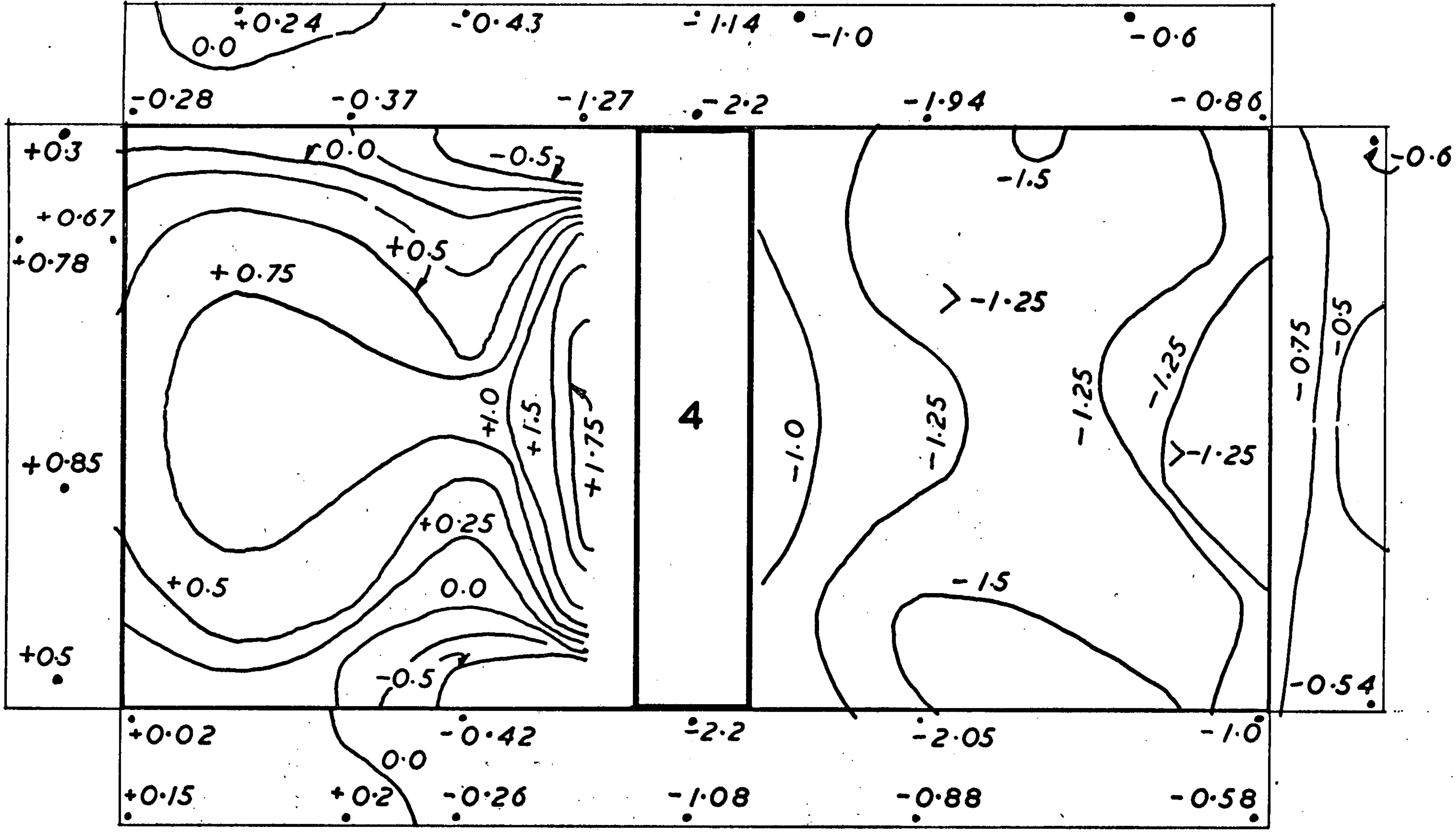


FIG 10 PRESSURE PATTERN GEOM 4 ⟶ WIND

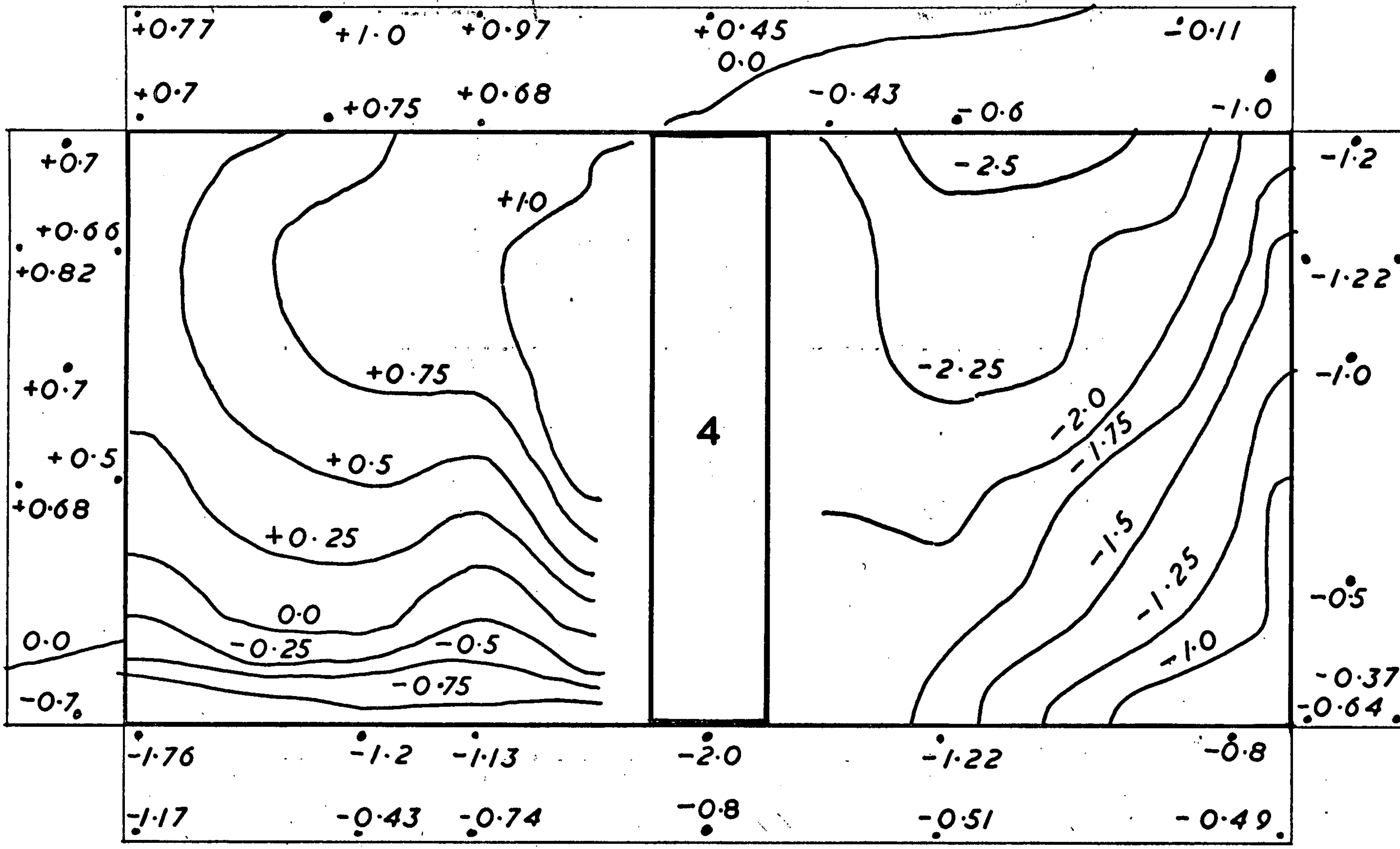


FIG 11 PRESSURE PATTERNS GEOM 4 ↘ WIND

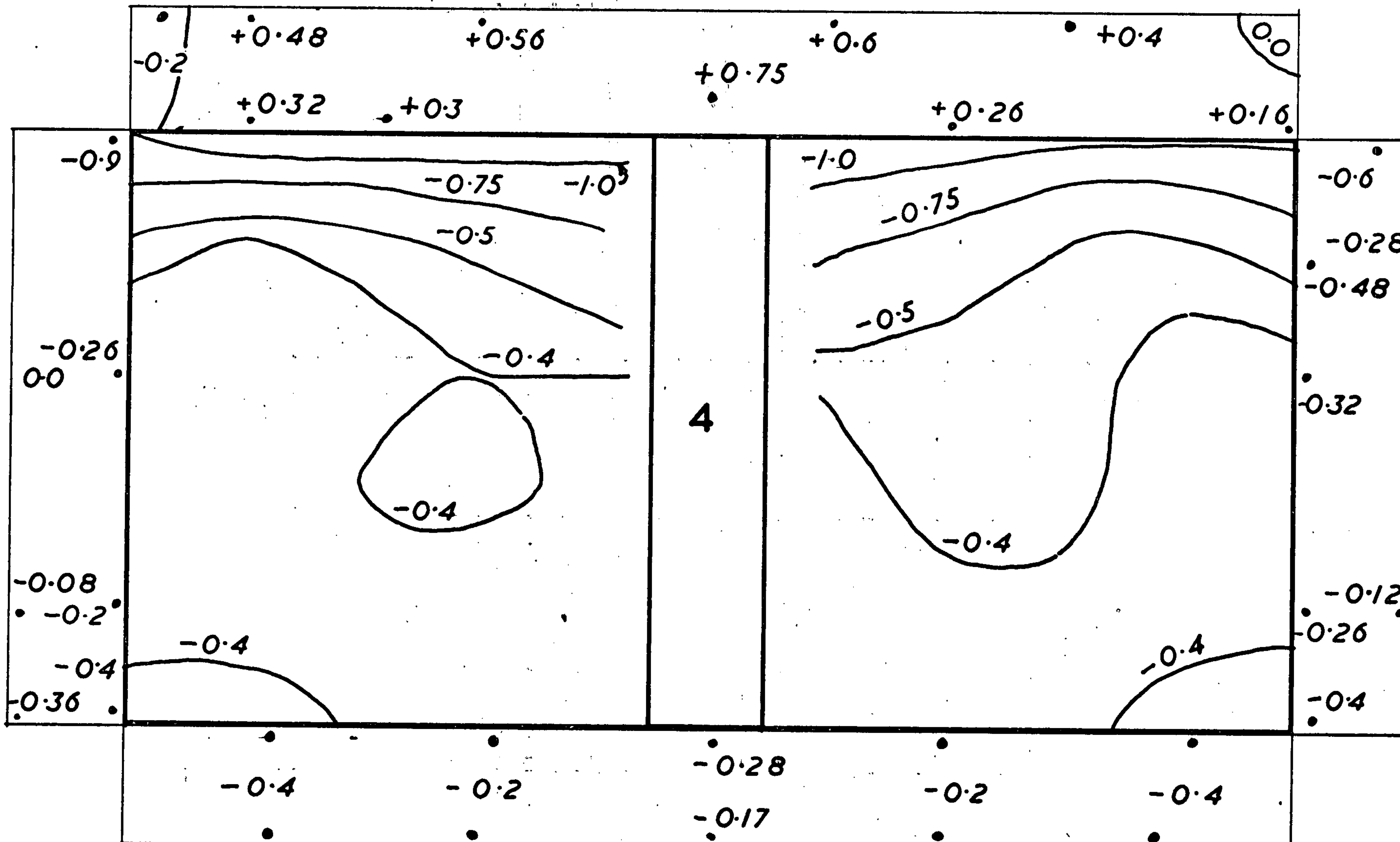


FIG 12 PRESSURE PATTERNS GEOM 4 ↓ WIND

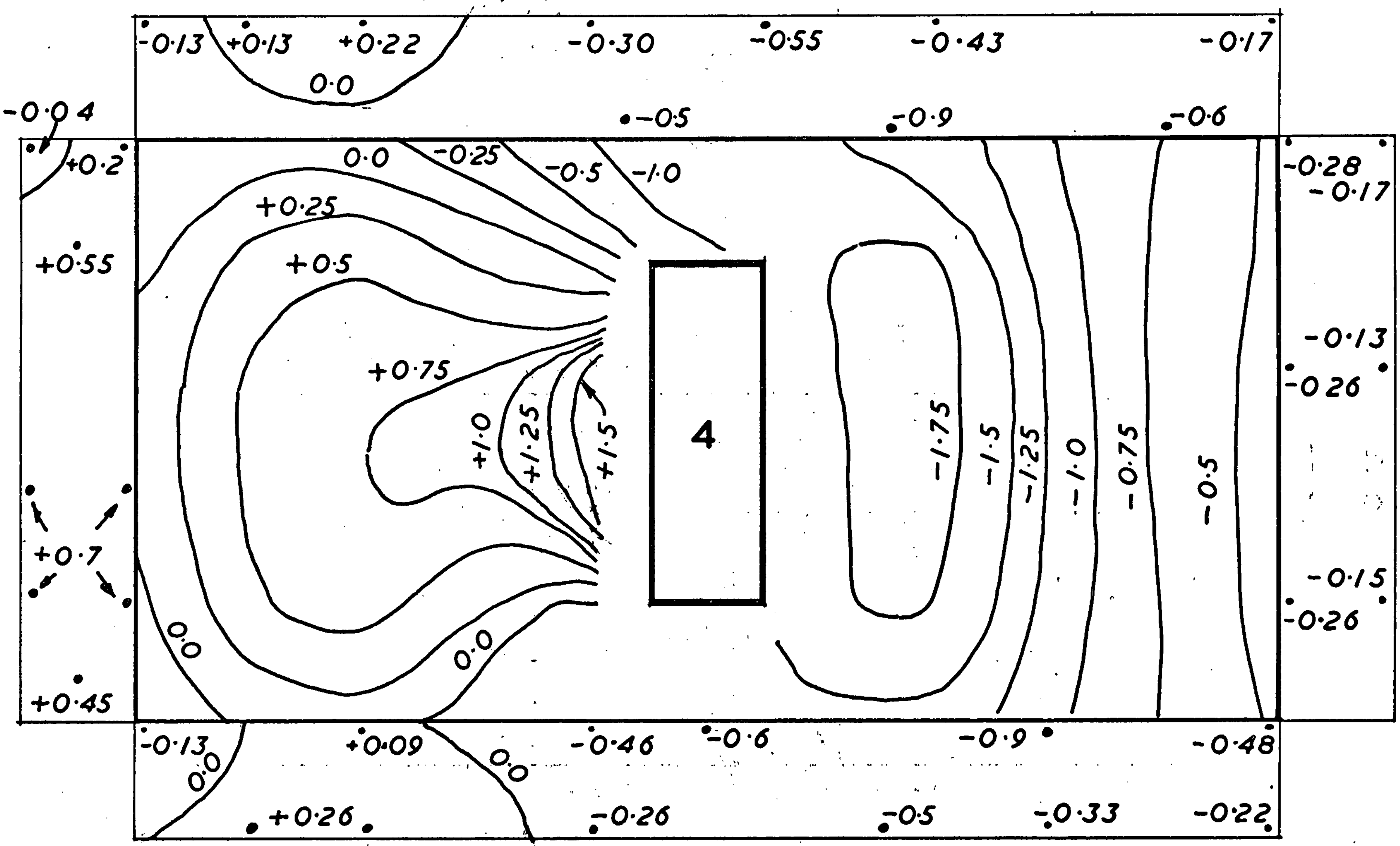


FIG 13 PRESSURE PATTERN GEOM 5 → WIND

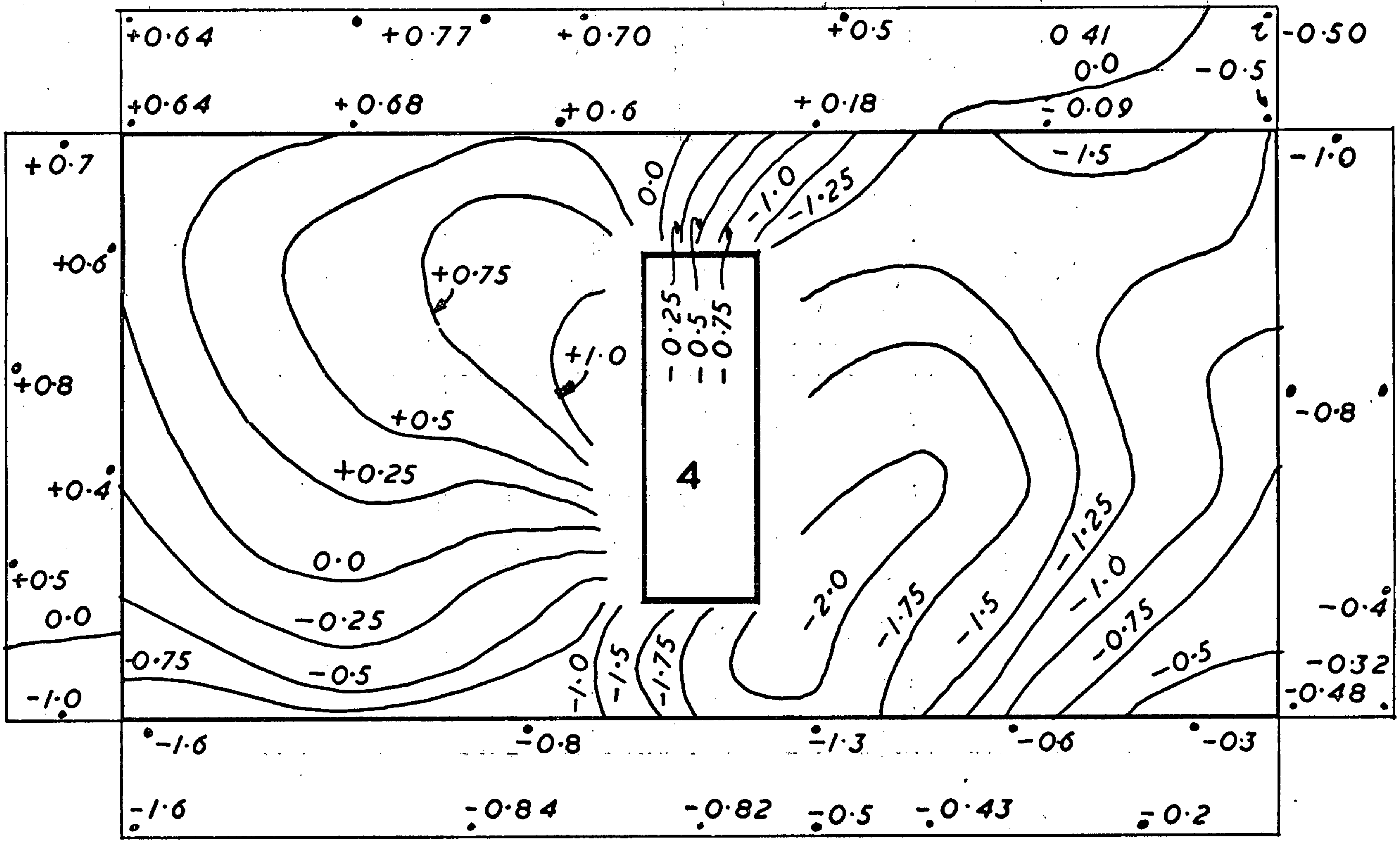


FIG 14 PRESSURE PATTERNS GEOM 5 ↘ WIND

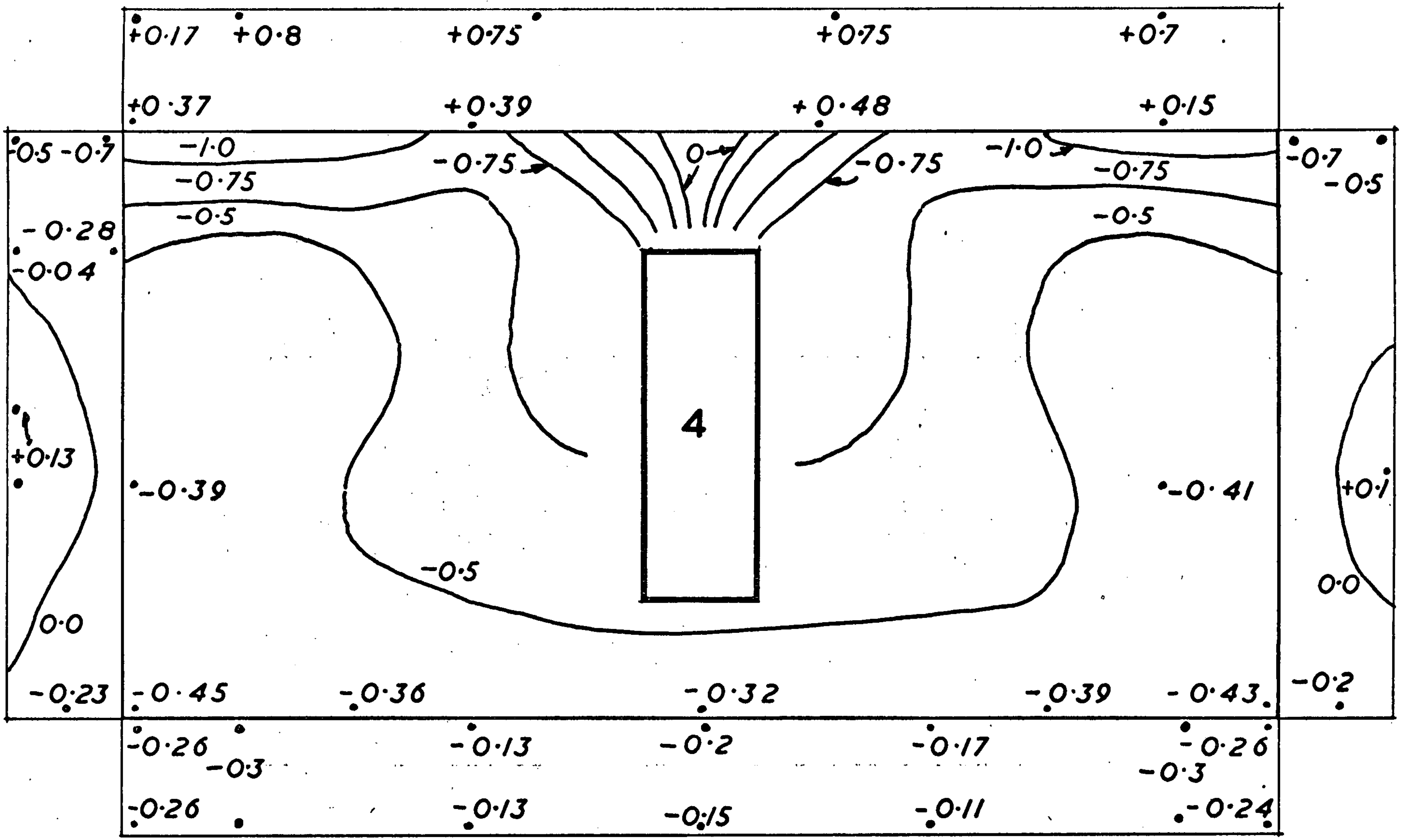


FIG 15 PRESSURE PATTERNS GEOM 5 ↓ WIND

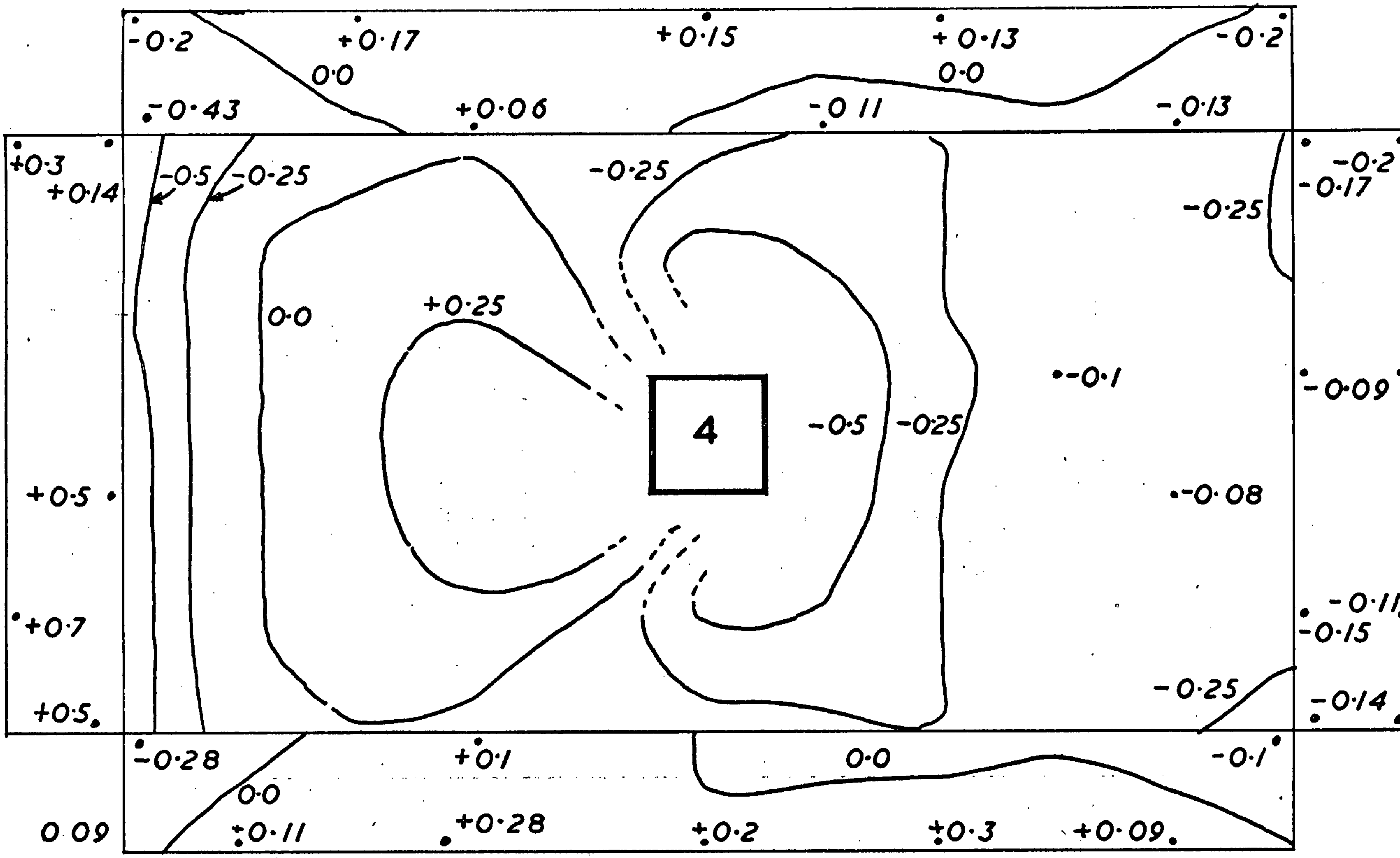


FIG 16 PRESSURE PATTERN GEOM 6 → WIND

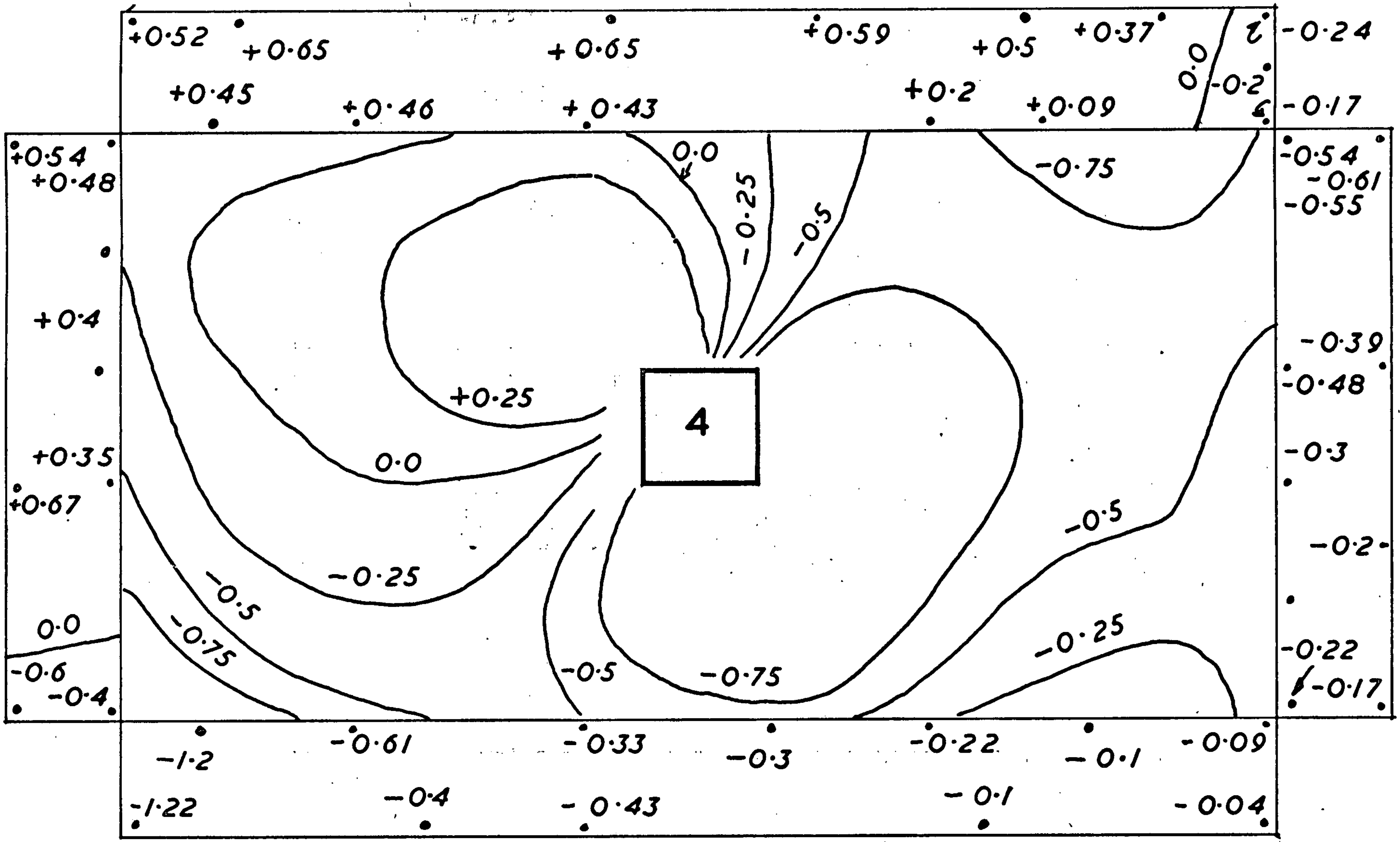


FIG 17 PRESSURE PATTERN GEOM 6 ↘ WIND

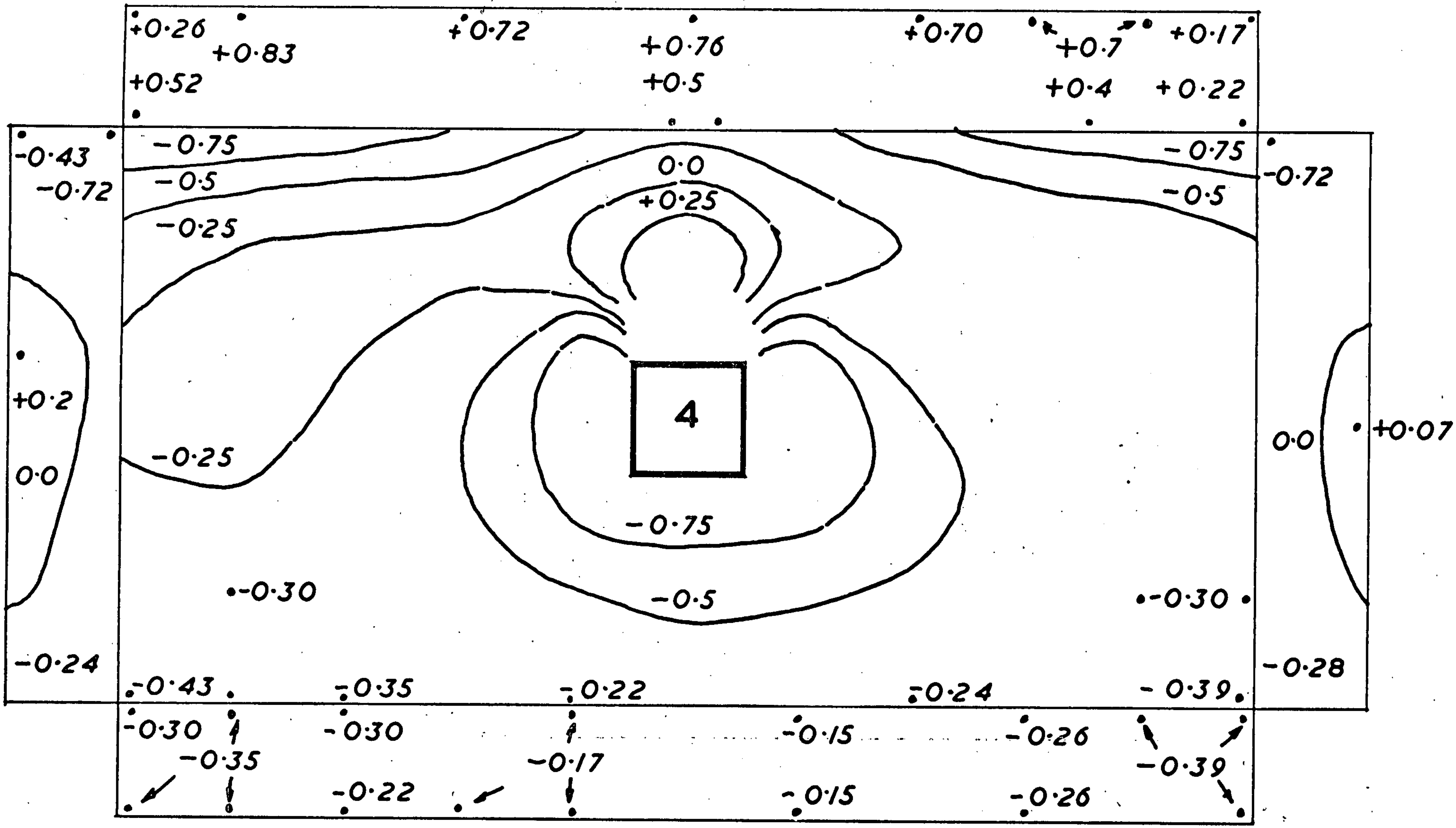


FIG 18 PRESSURE PATTERNS GEOM 6 ↓ WIND

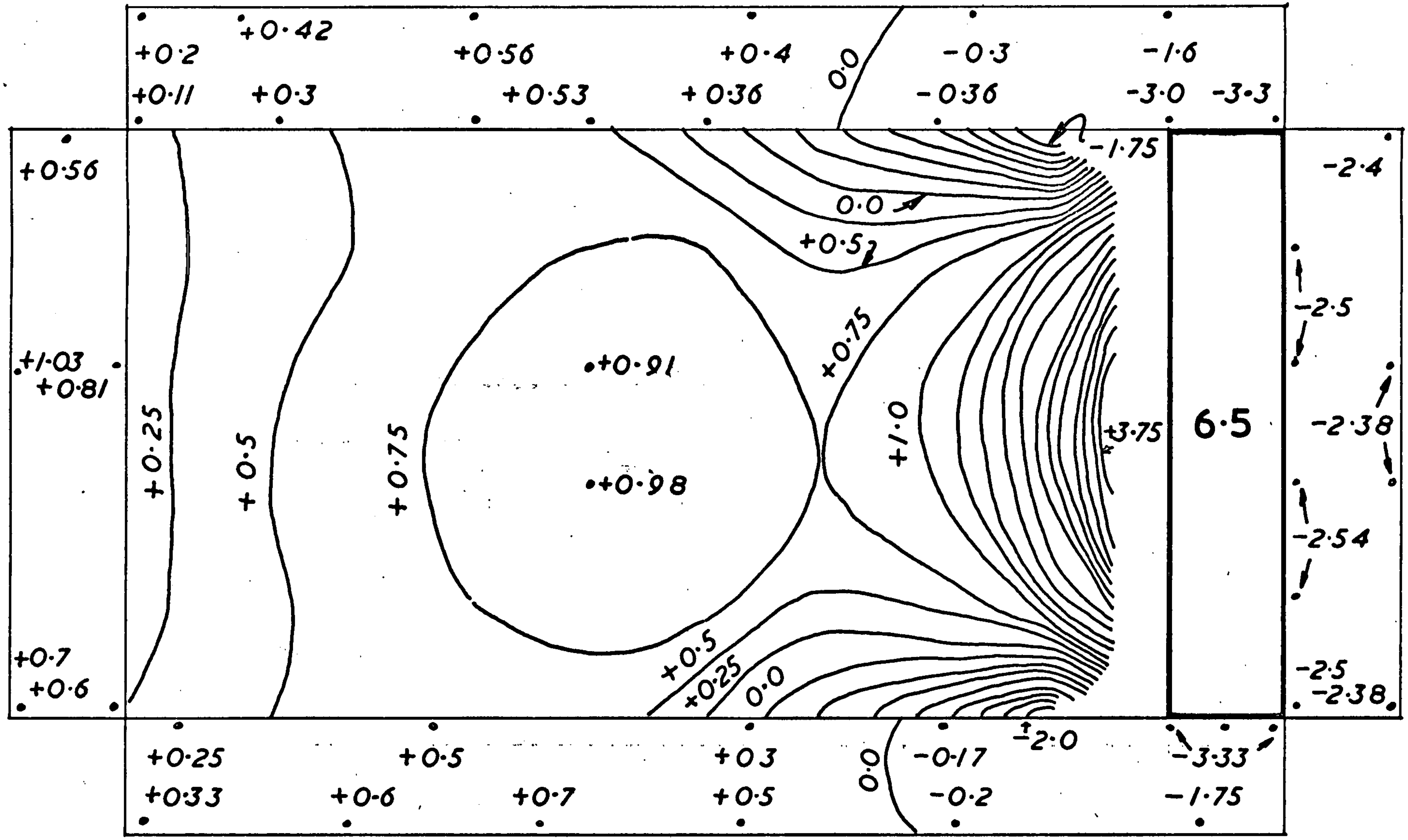


FIG 19 PRESSURE PATTERN GEOM 7 → WIND

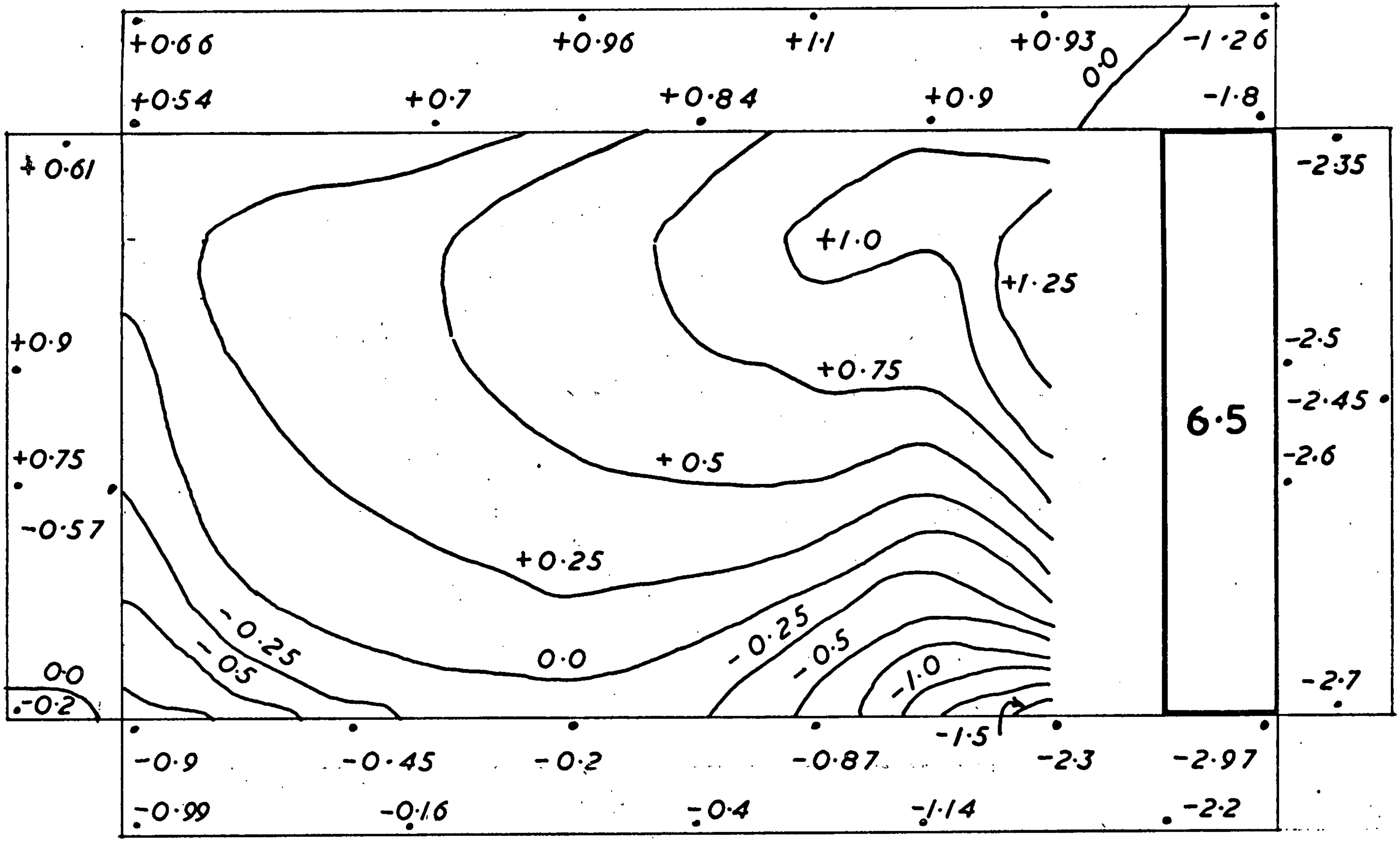


FIG 20 PRESSURE PATTERN GEOM 7 ↘ WIND

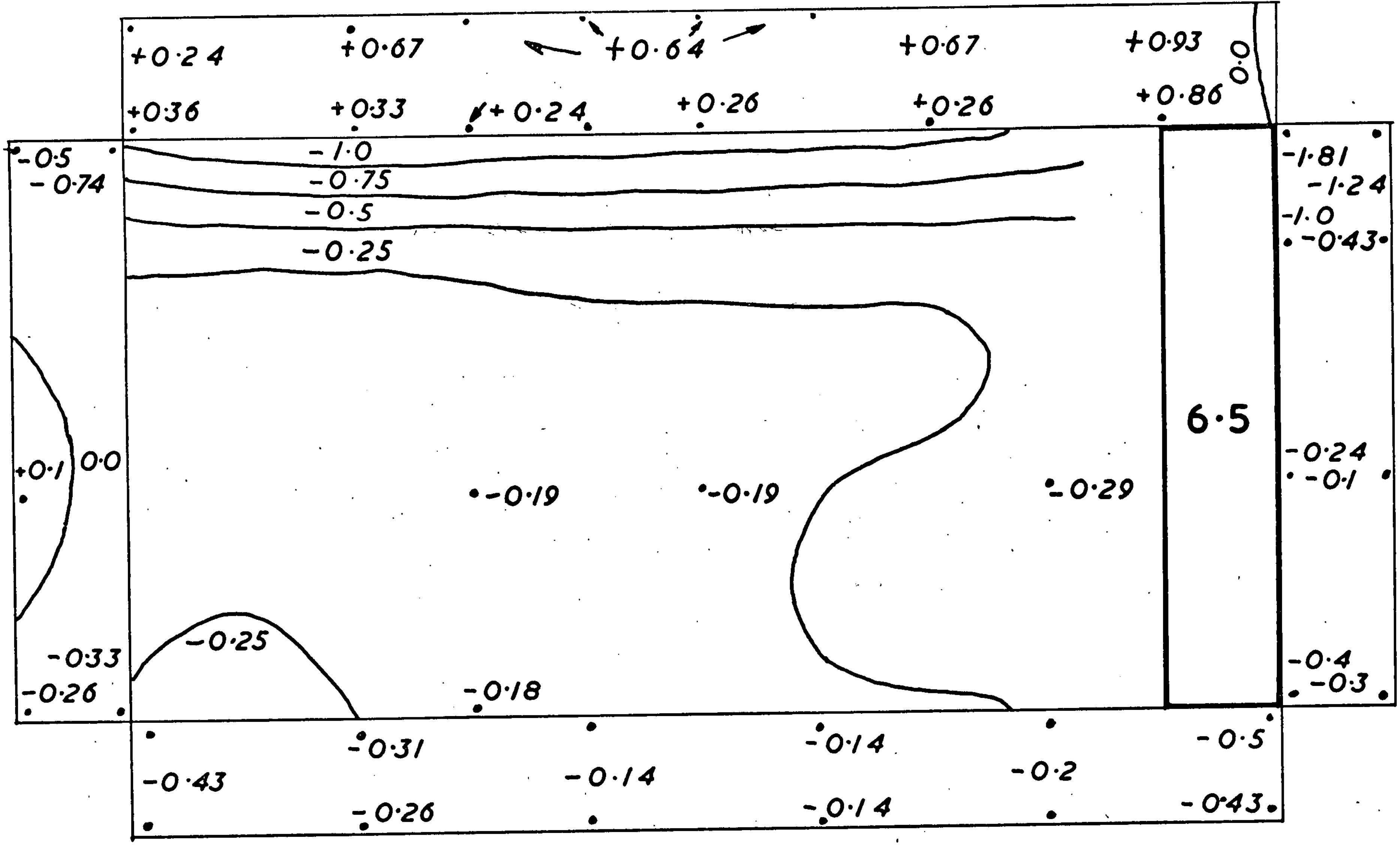


FIG 21 PRESSURE PATTERN GEOM 7 ↓ WIND

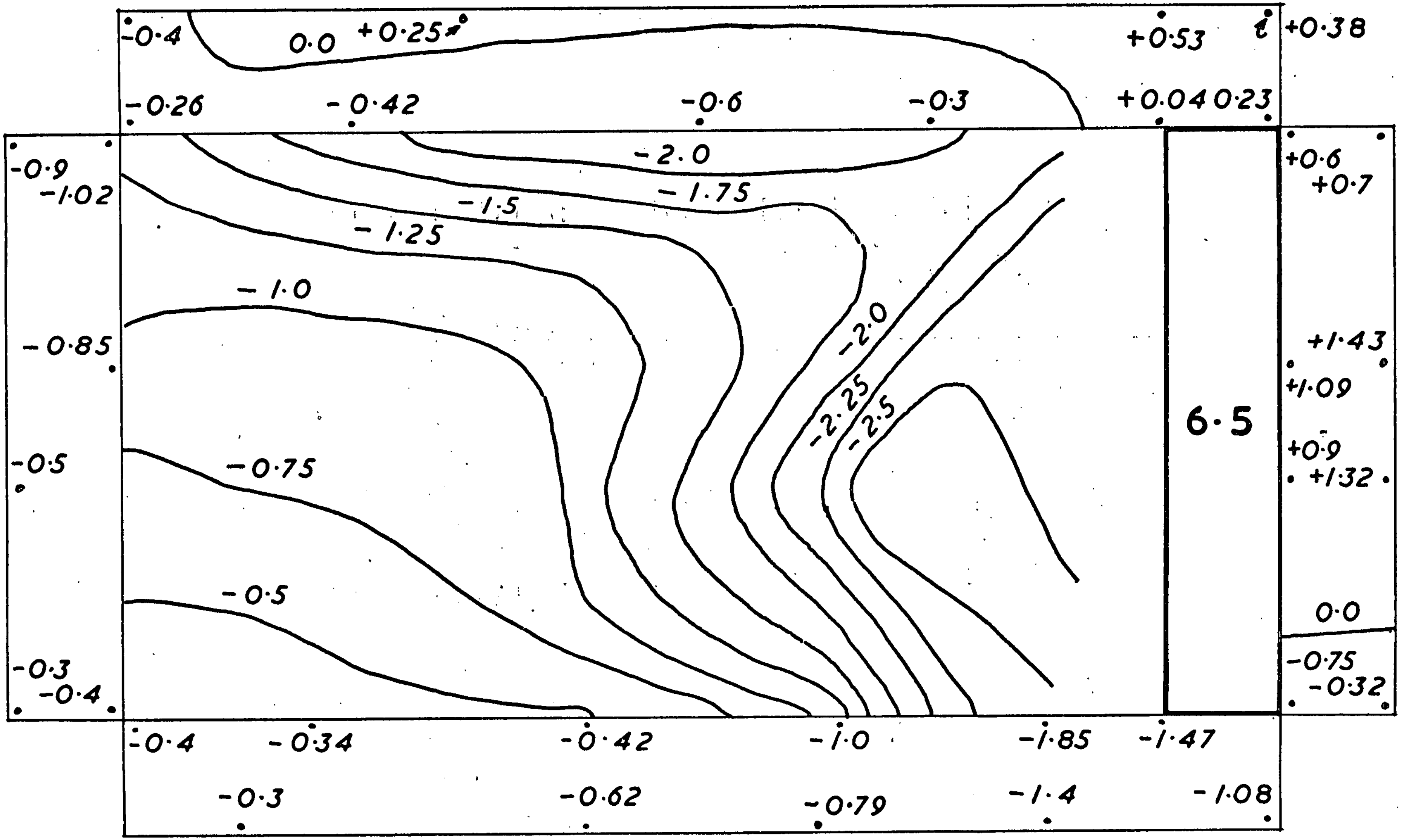


FIG 22 PRESSURE PATTERN GEOM 7 ↙ WIND

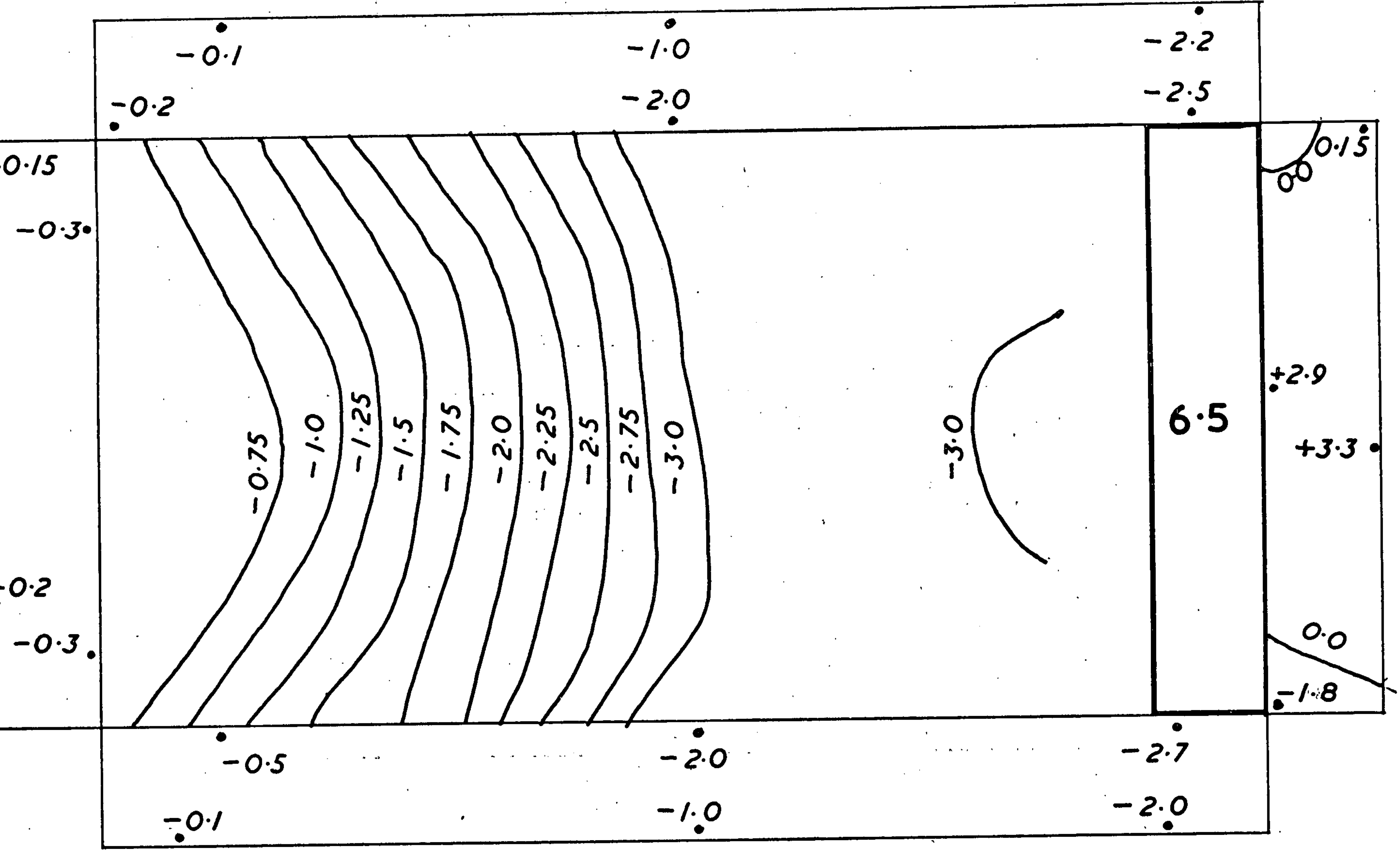


FIG 23 PRESSURE PATTERN GEOM 7 ← WIND

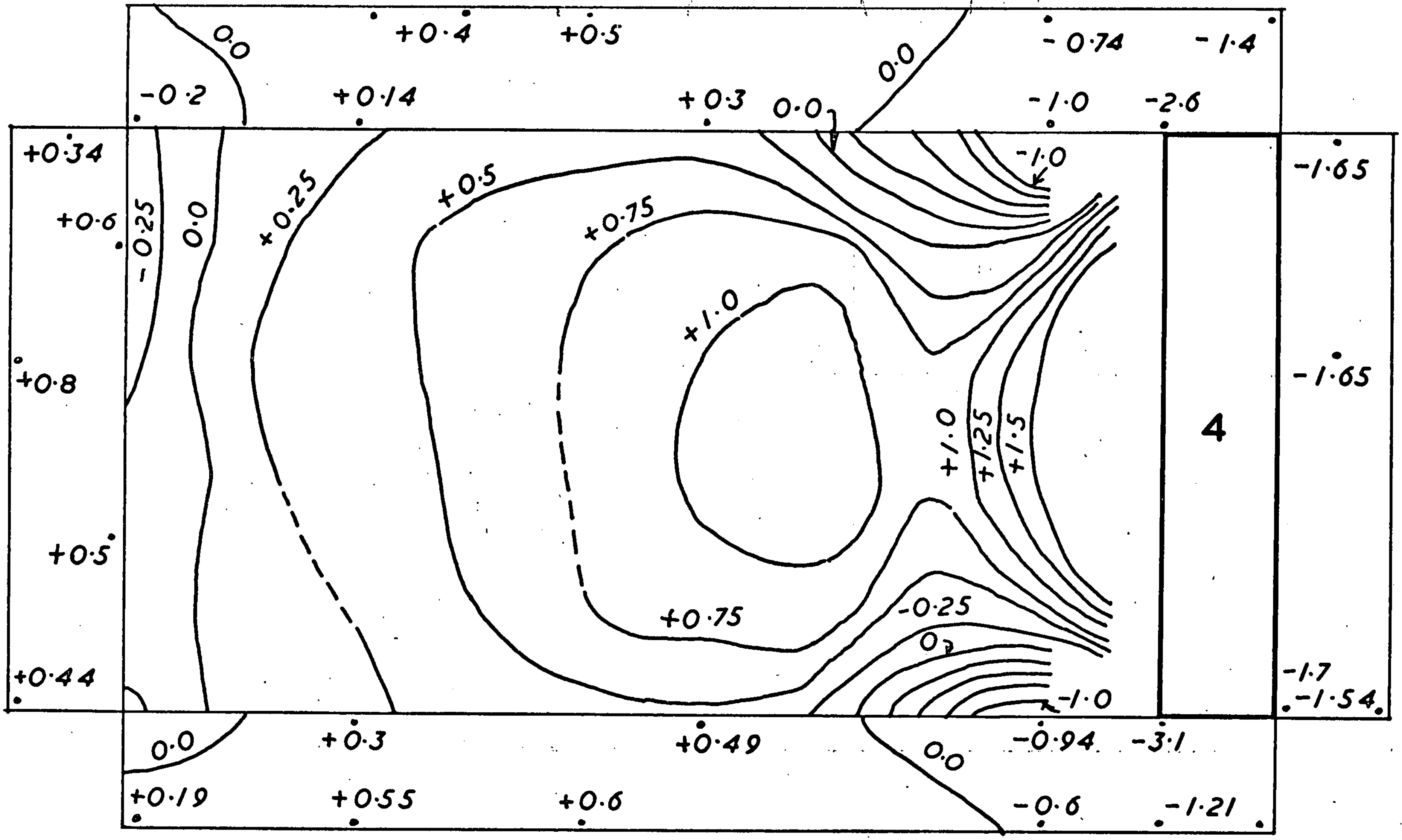


FIG 24 PRESSURE PATTERN GEOM 8

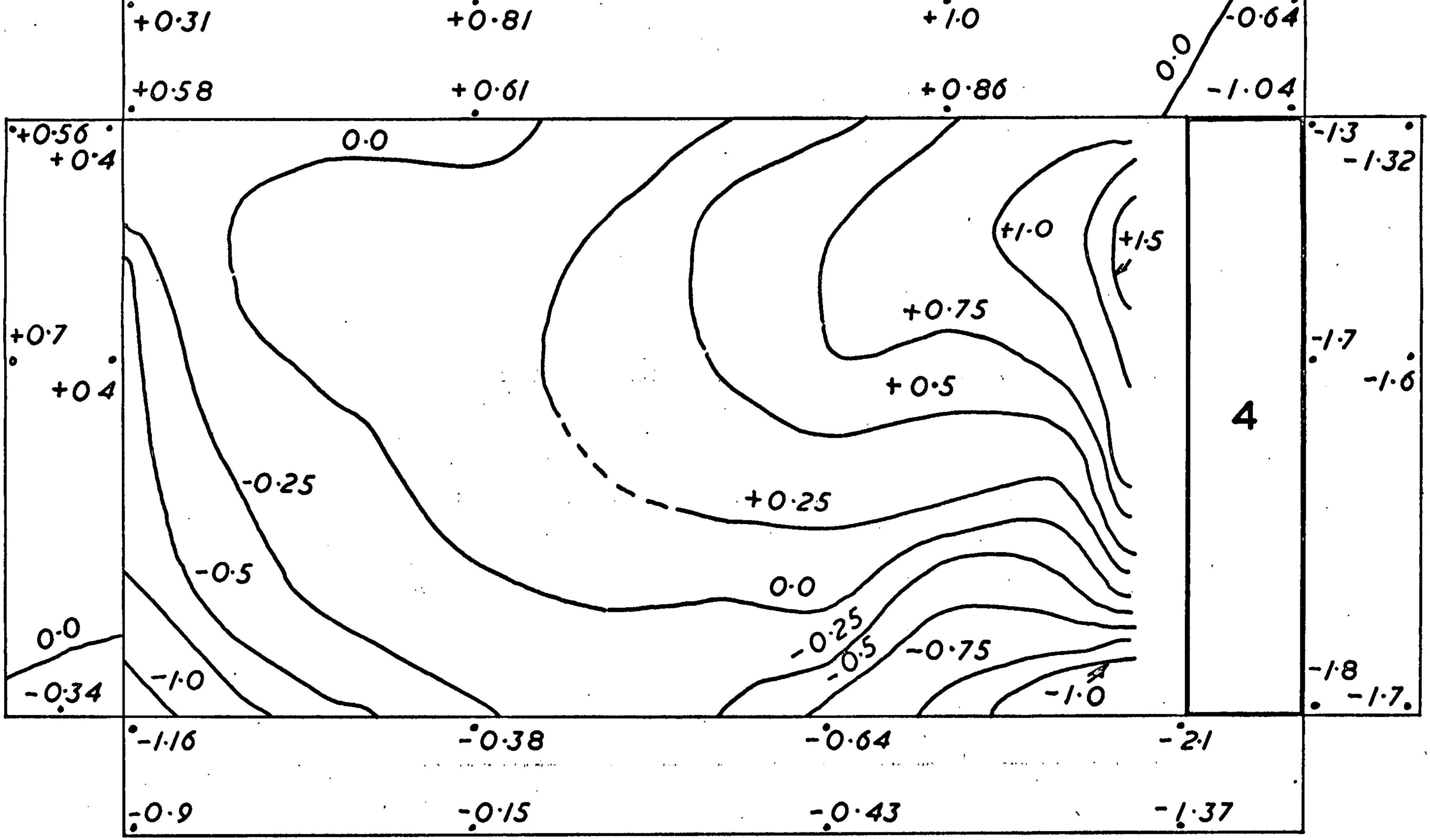


FIG 25 PRESSURE PATTERN GEOM 8 ↘ WIND

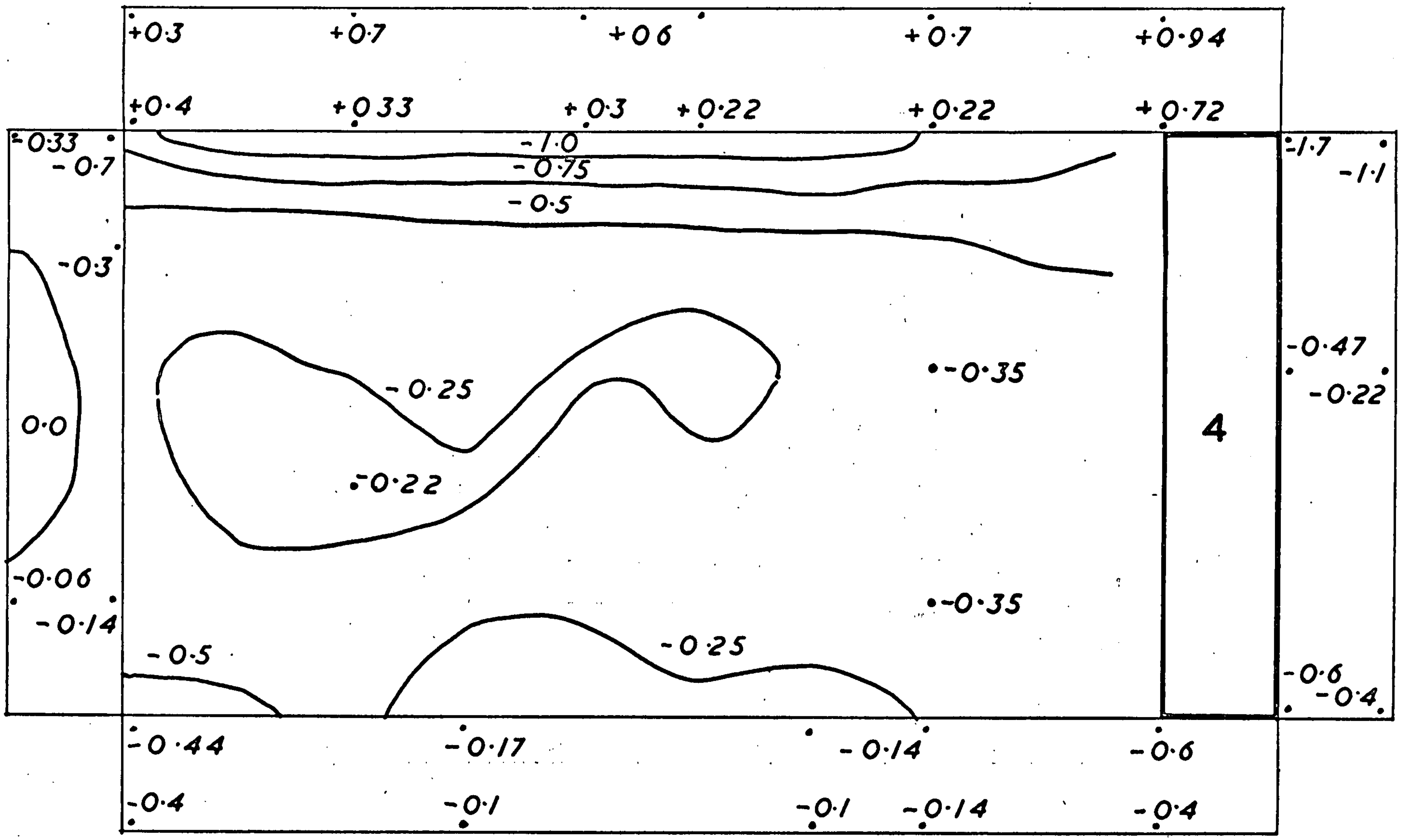


FIG 26 PRESSURE PATTERN GEOM 8 ↓ WIND

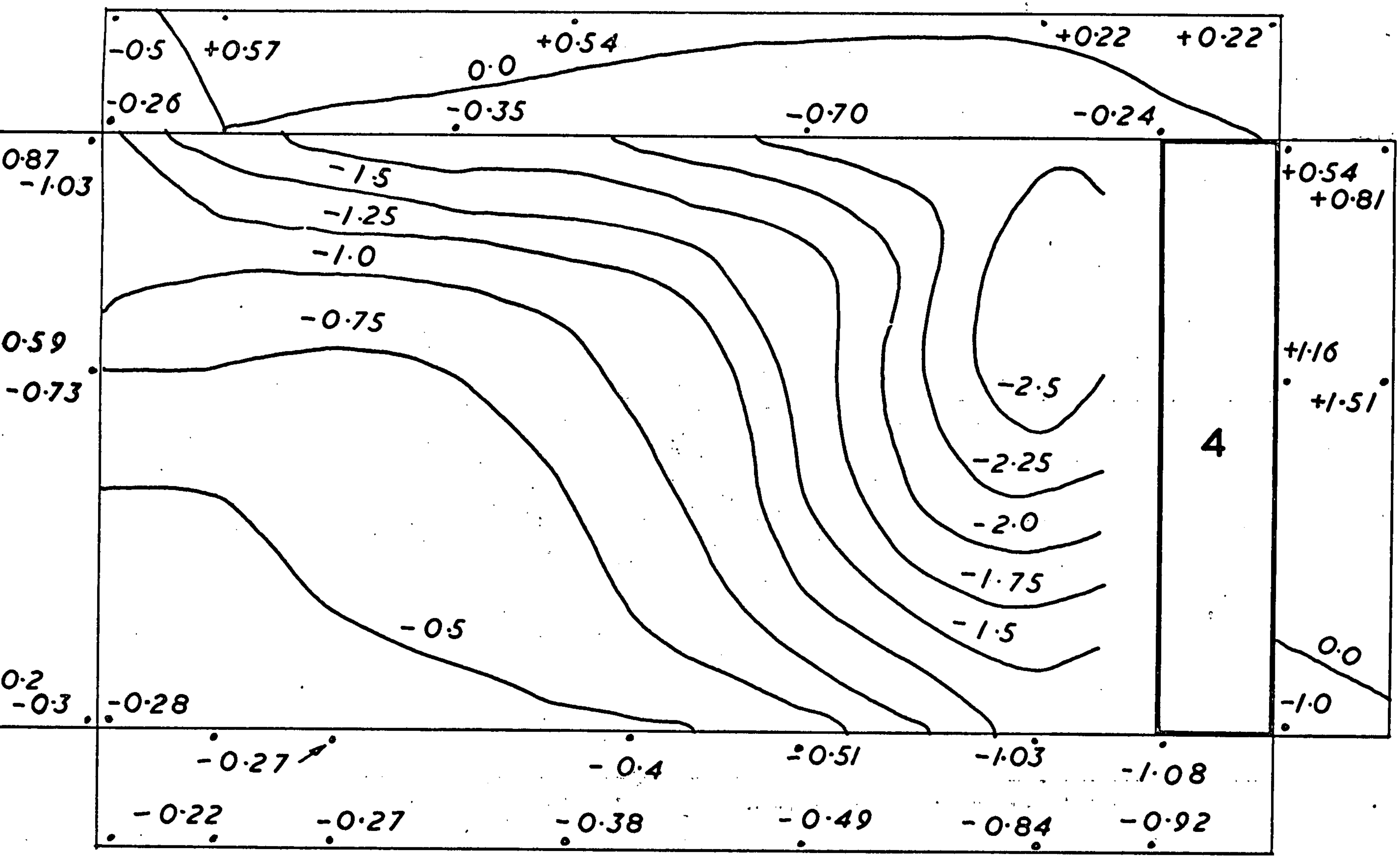


FIG 27 PRESSURE PATTERN GEOM 8 ↙ WIND

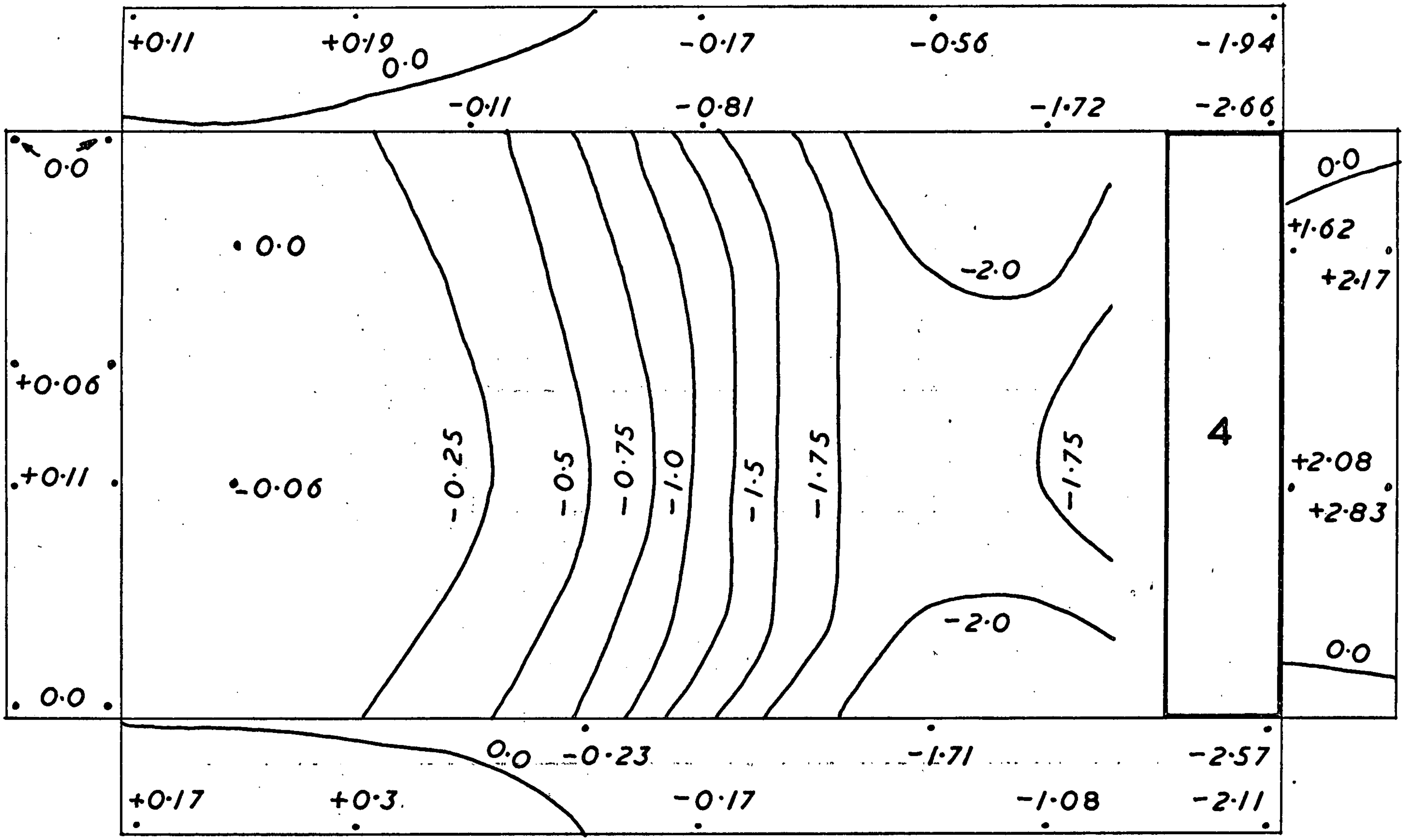


FIG 28 PRESSURE PATTERN GEOM 8 ← WIND

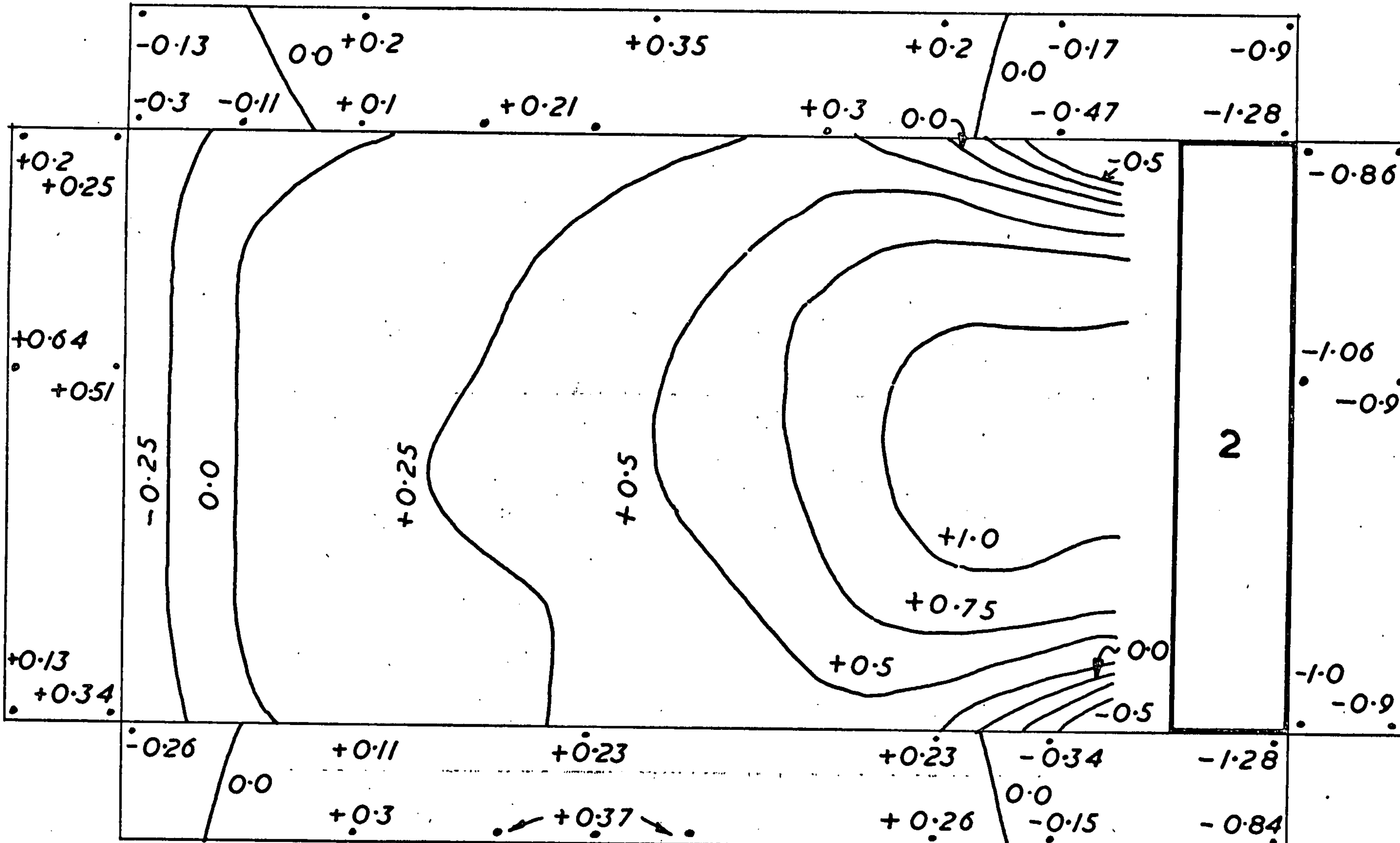


FIG 29 PRESSURE PATTERNS GEOM 9 → WIND

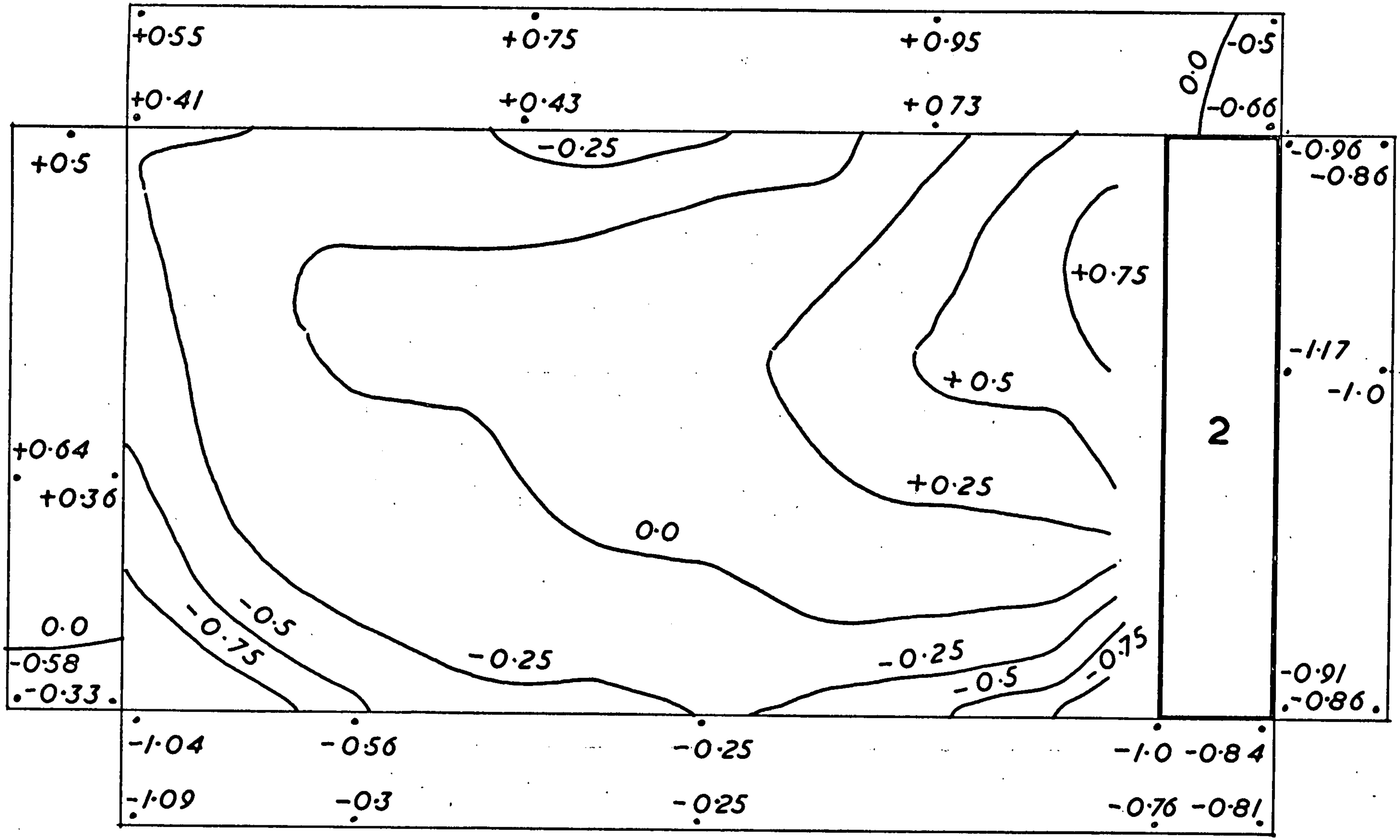


FIG 30 PRESSURE PATTERN GEOM 9

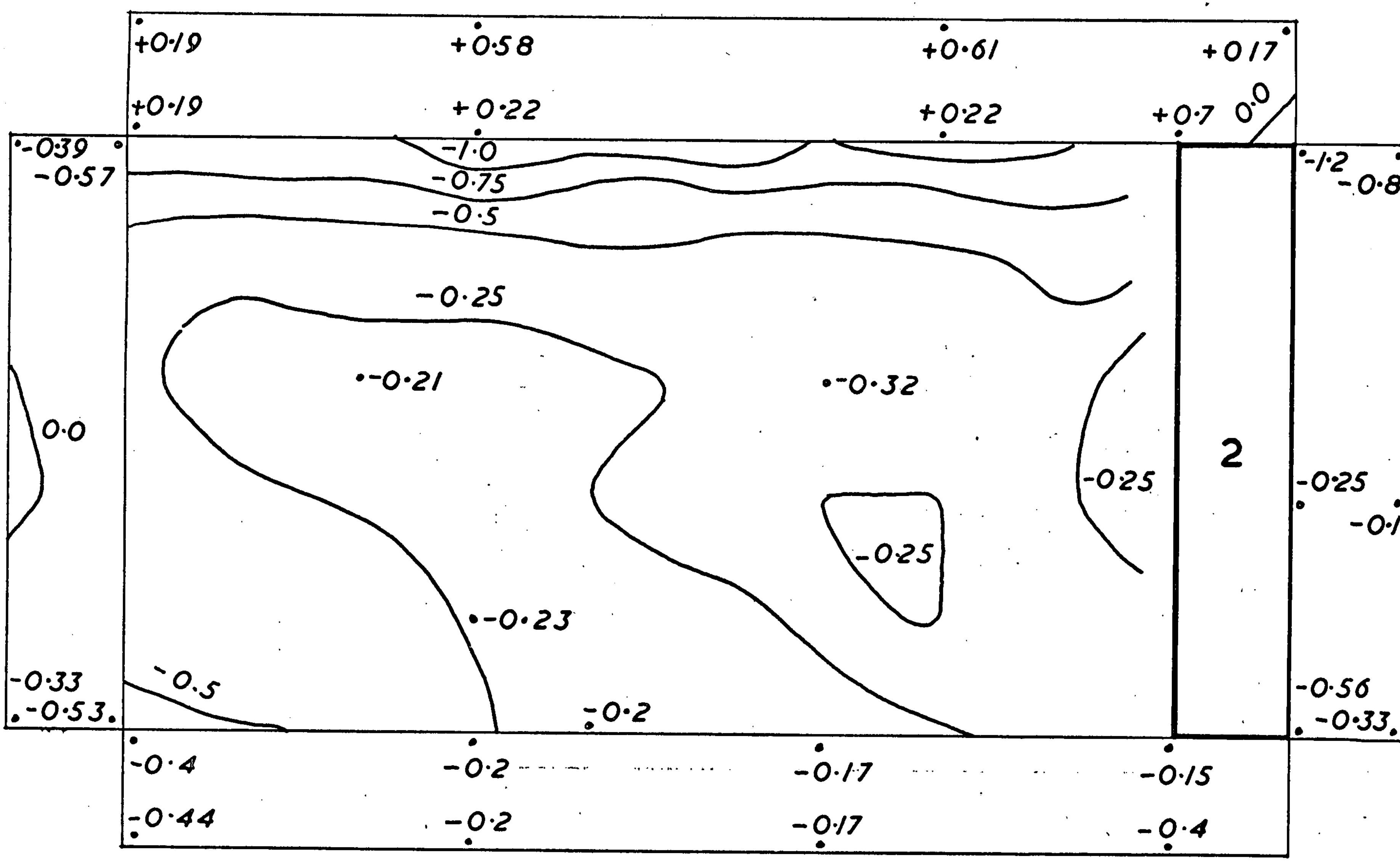


FIG 31 PRESSURE PATTERN GEOM 9 ↓ WIND

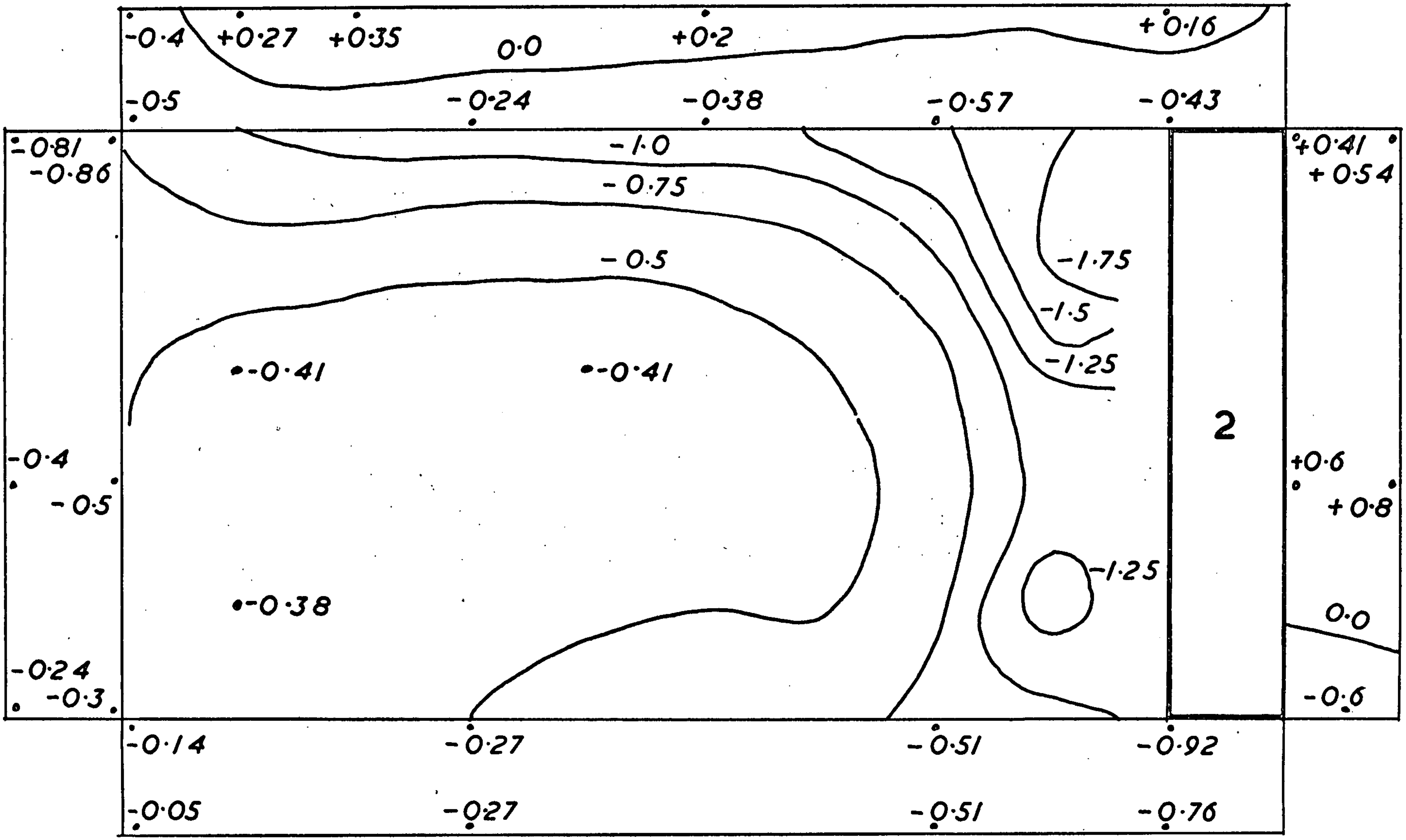


FIG 32 PRESSURE PATTERN GEOM 9 ↙ WIND

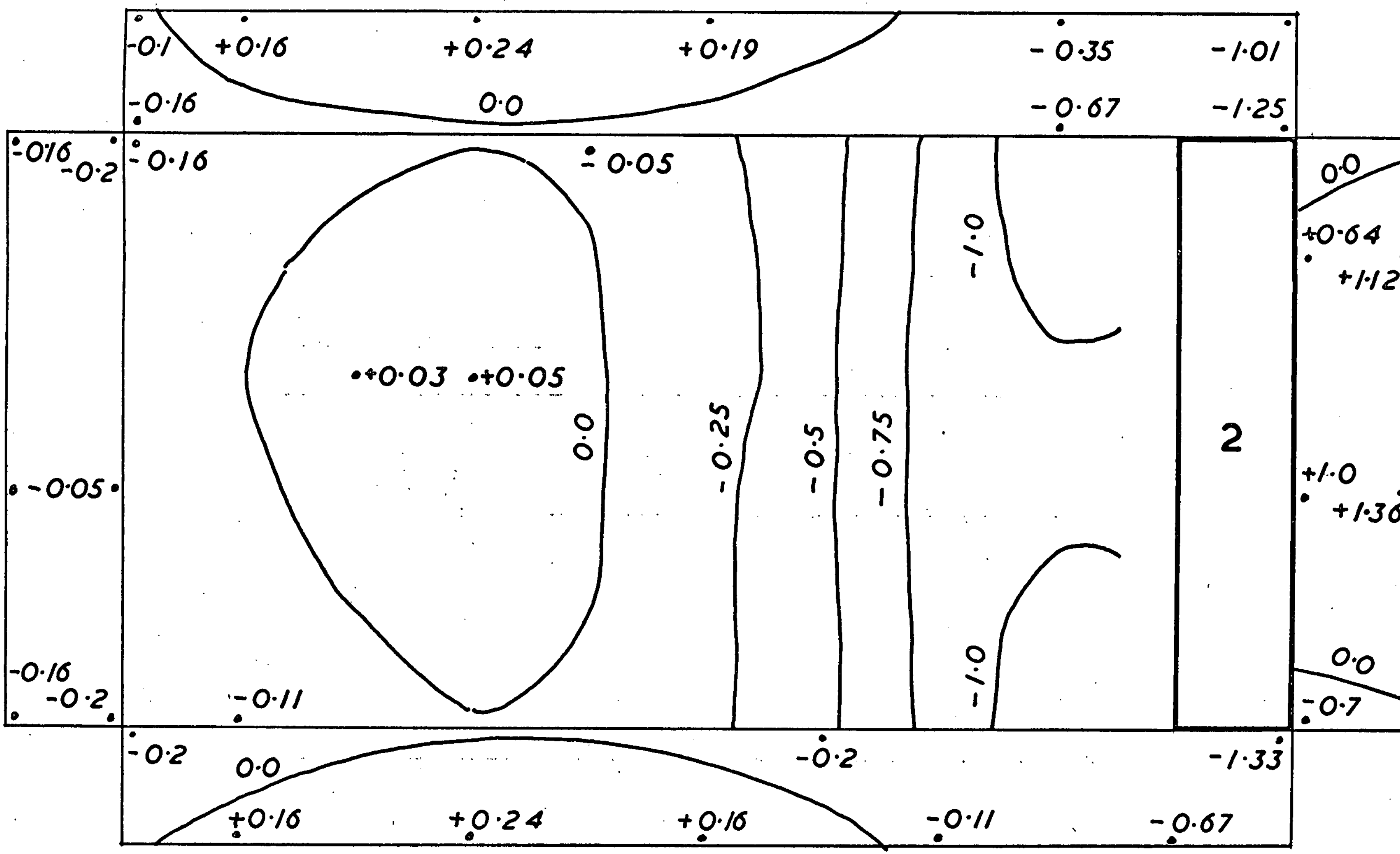


FIG 33 PRESSURE PATTERN GEOM 9 ← WIND

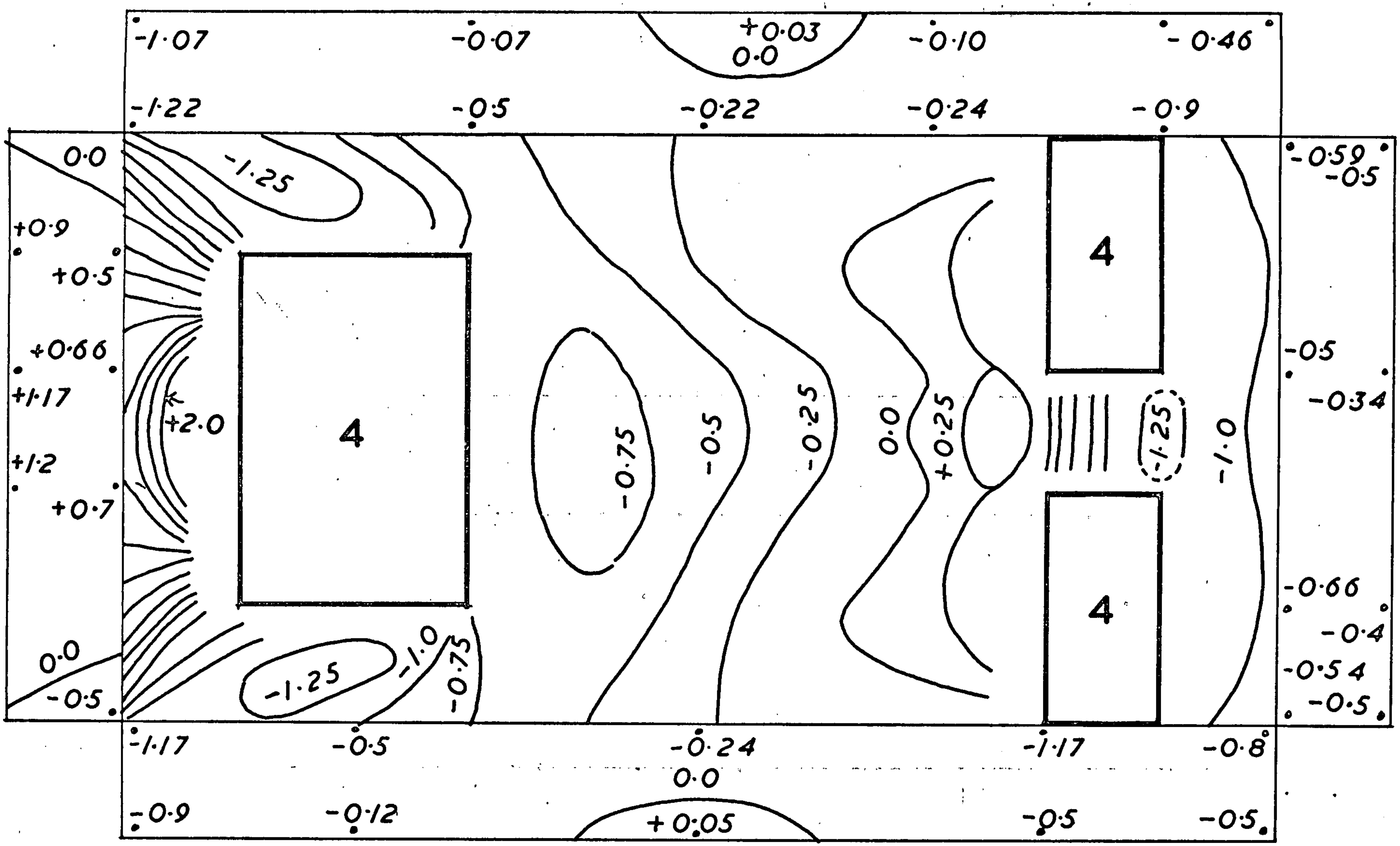


FIG 34 PRESSURE PATTERN GEOM 10 → WIND

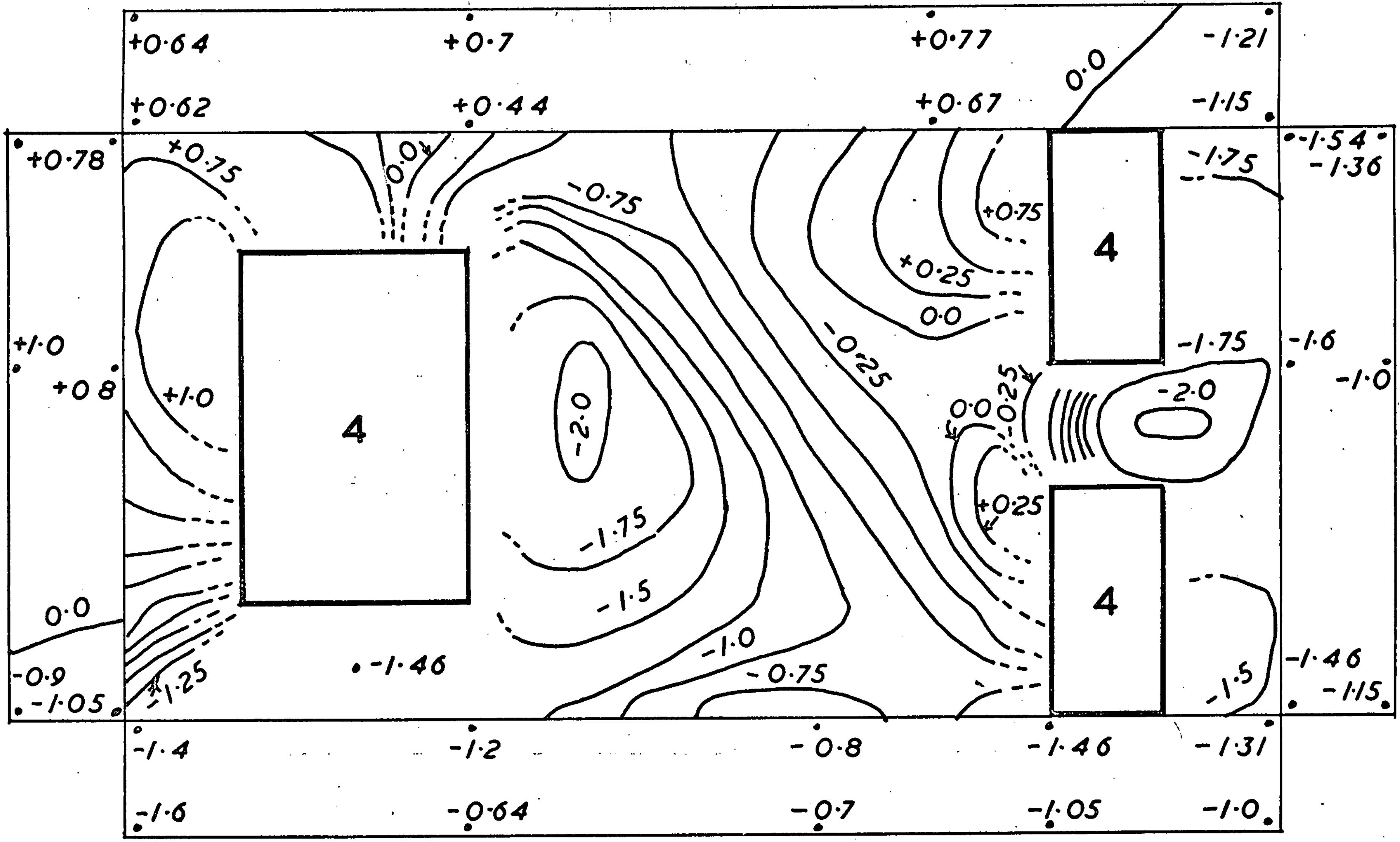


FIG 35 PRESSURE PATTERN GEOM 10 ↘ WIND

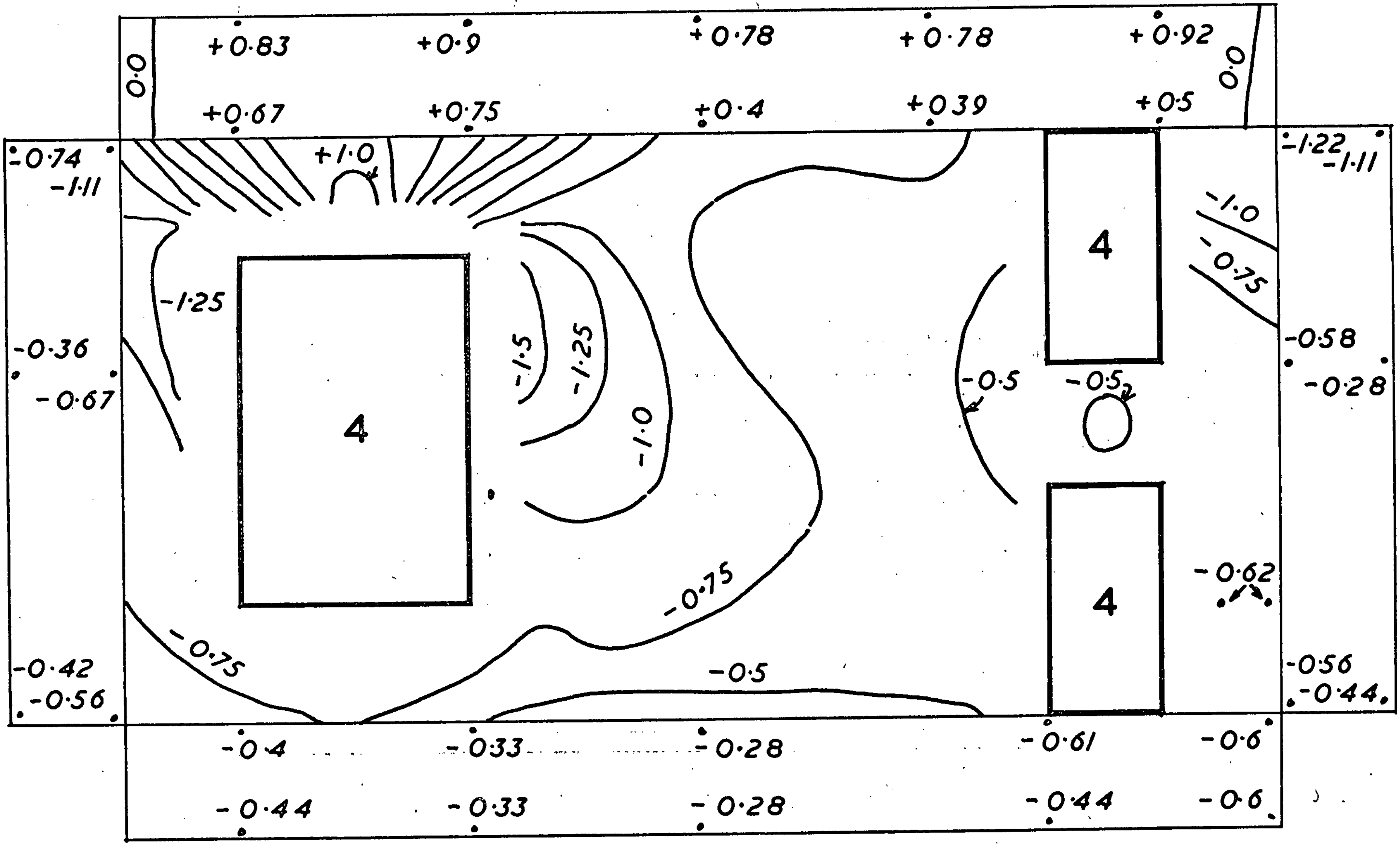


FIG 36 PRESSURE PATTERN GEOM 10

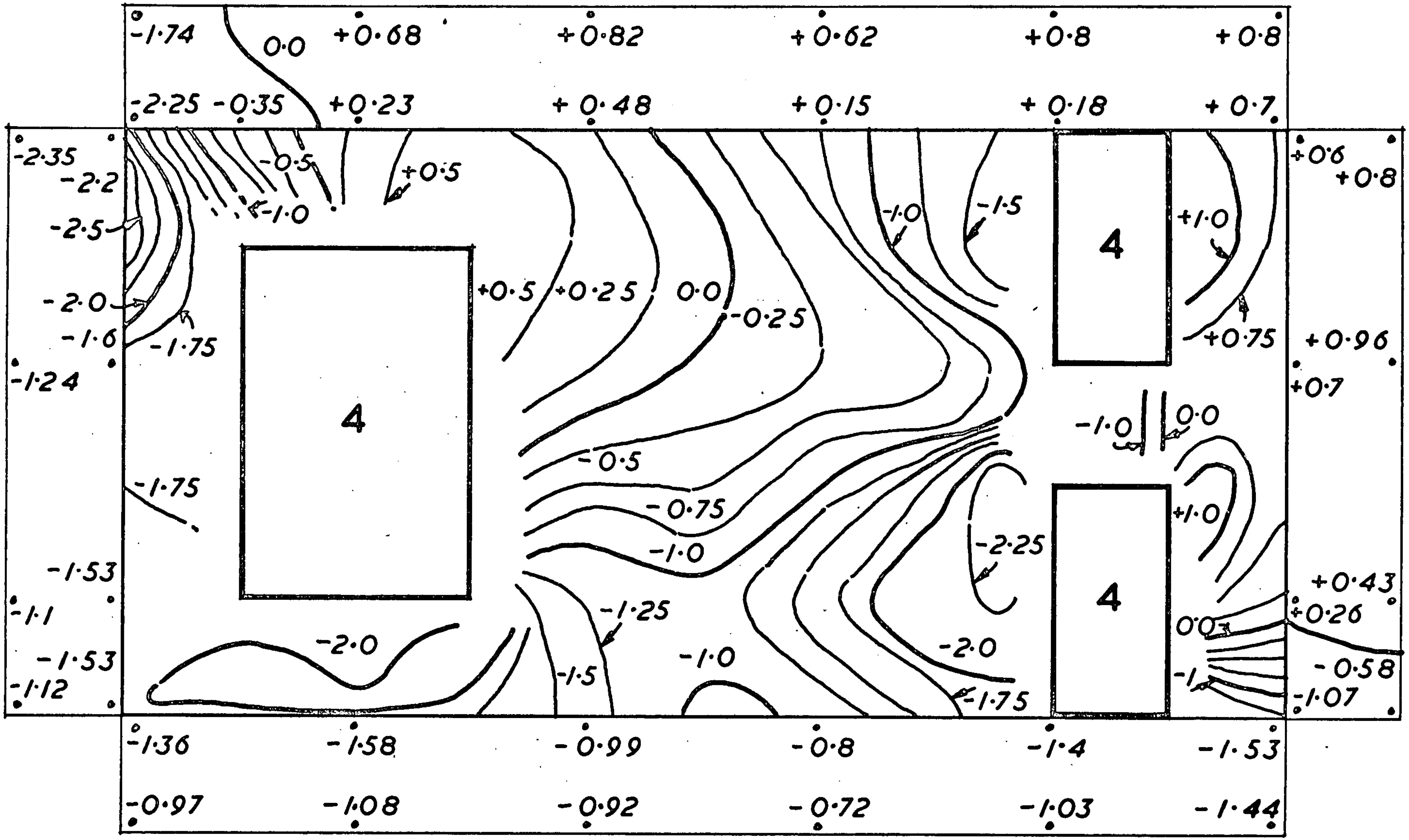


FIG 37 PRESSURE PATTERN GEOM 10 ↙ WIND

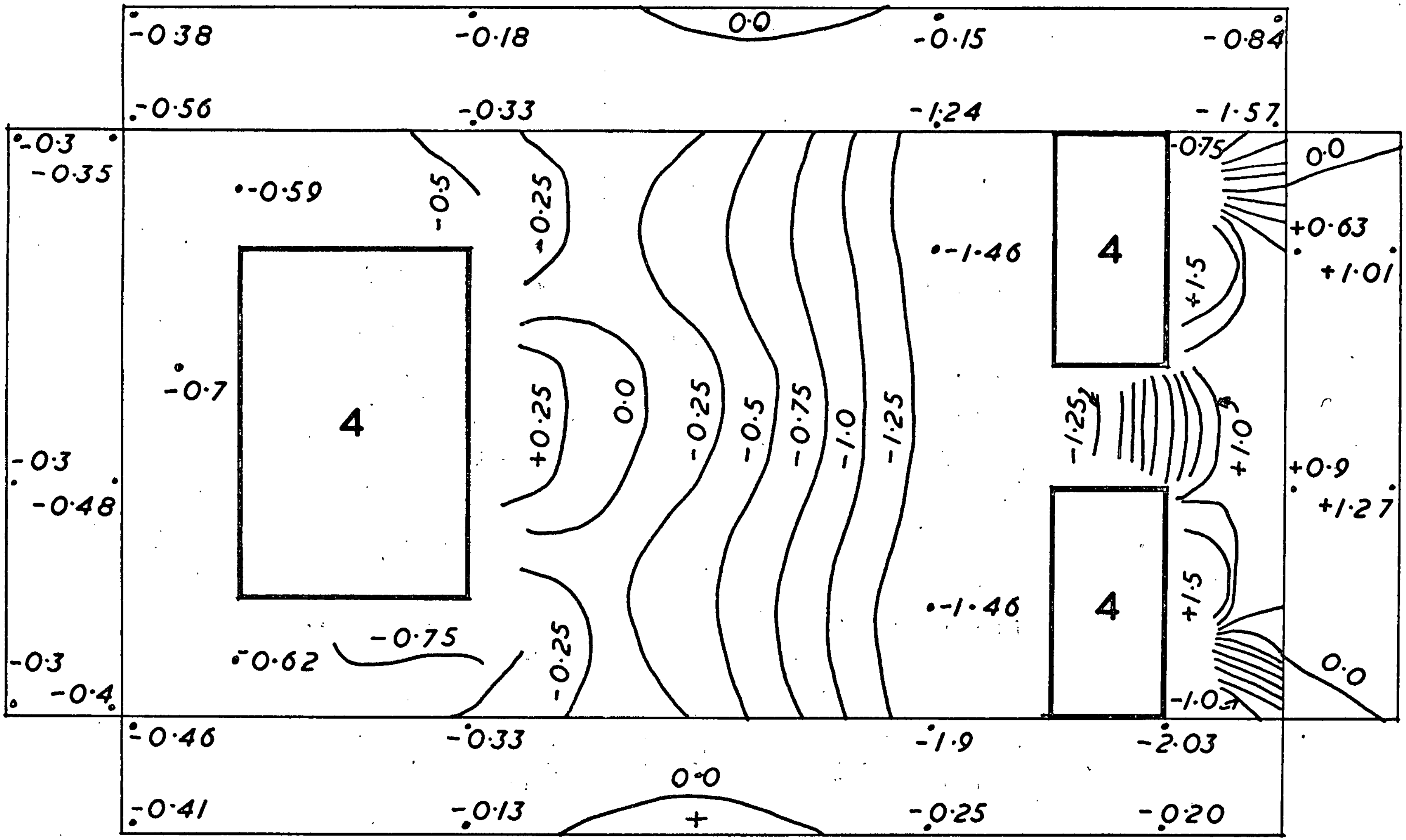


FIG 38 PRESSURE PATTERN GEOM 10 ← WIND

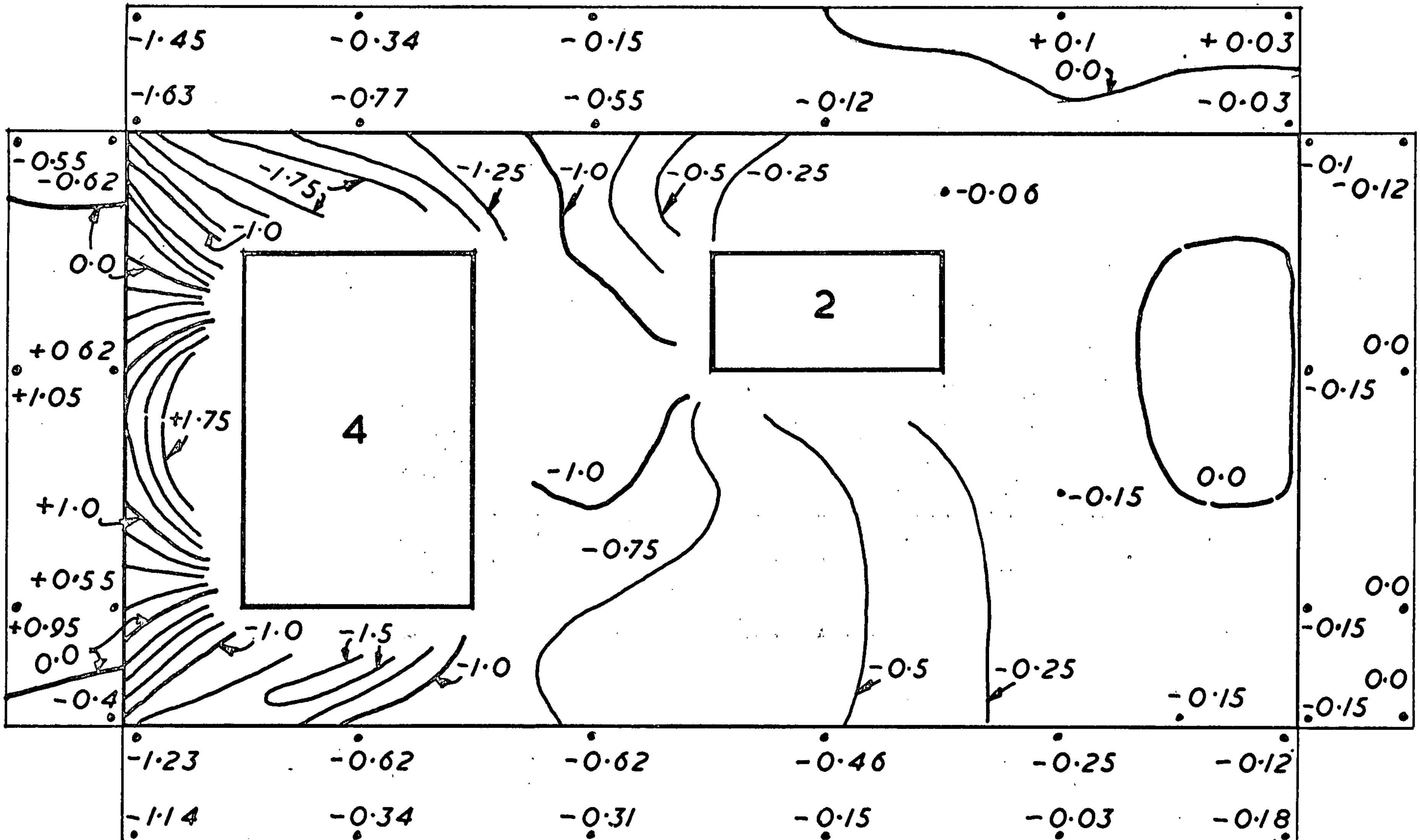


FIG 39 PRESSURE PATTERN GEOM II → WIND

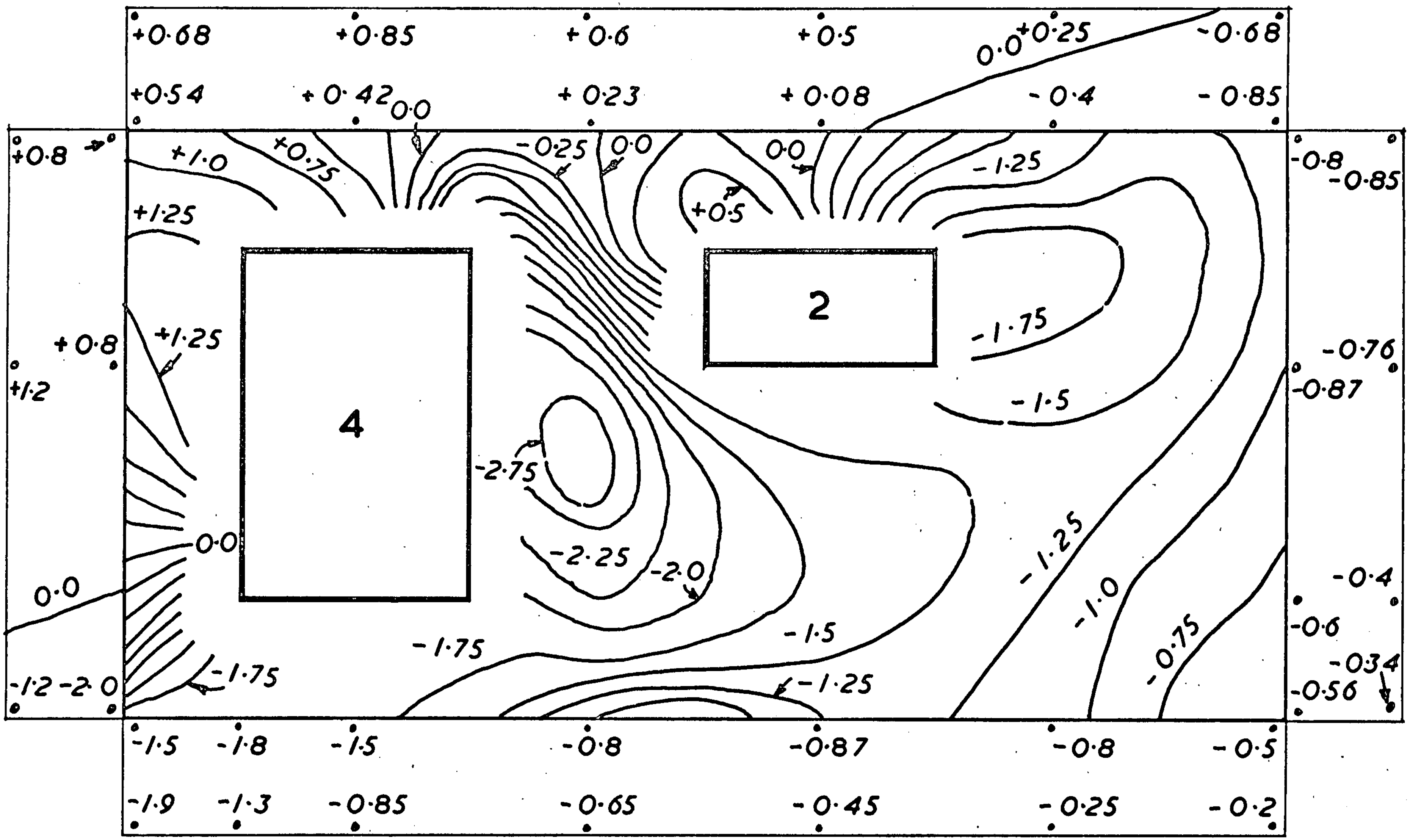


FIG 40 PRESSURE PATTERN GEOM II ↘ WIND

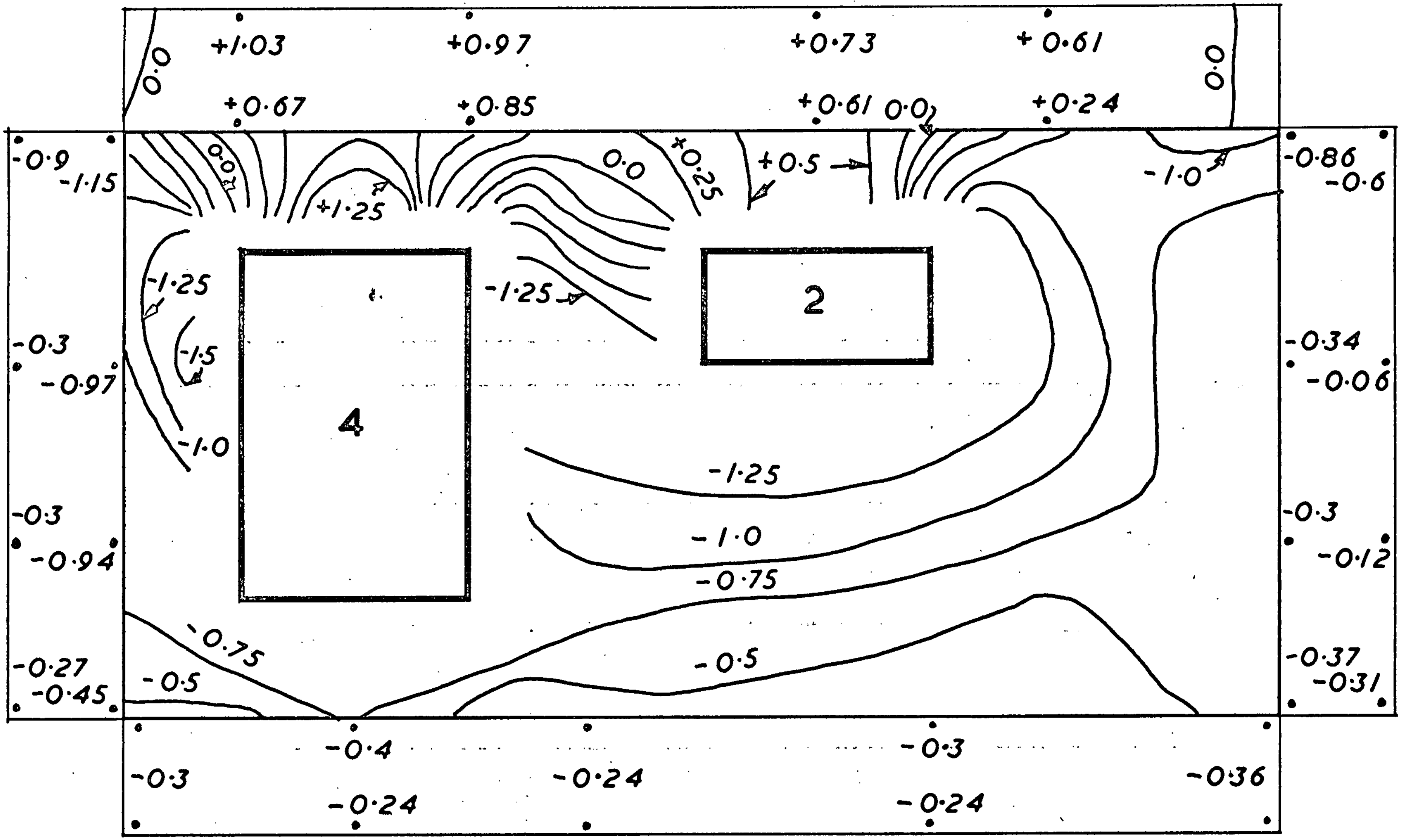


FIG 41 PRESSURE PATTERN GEOM 11 ↓ WIND

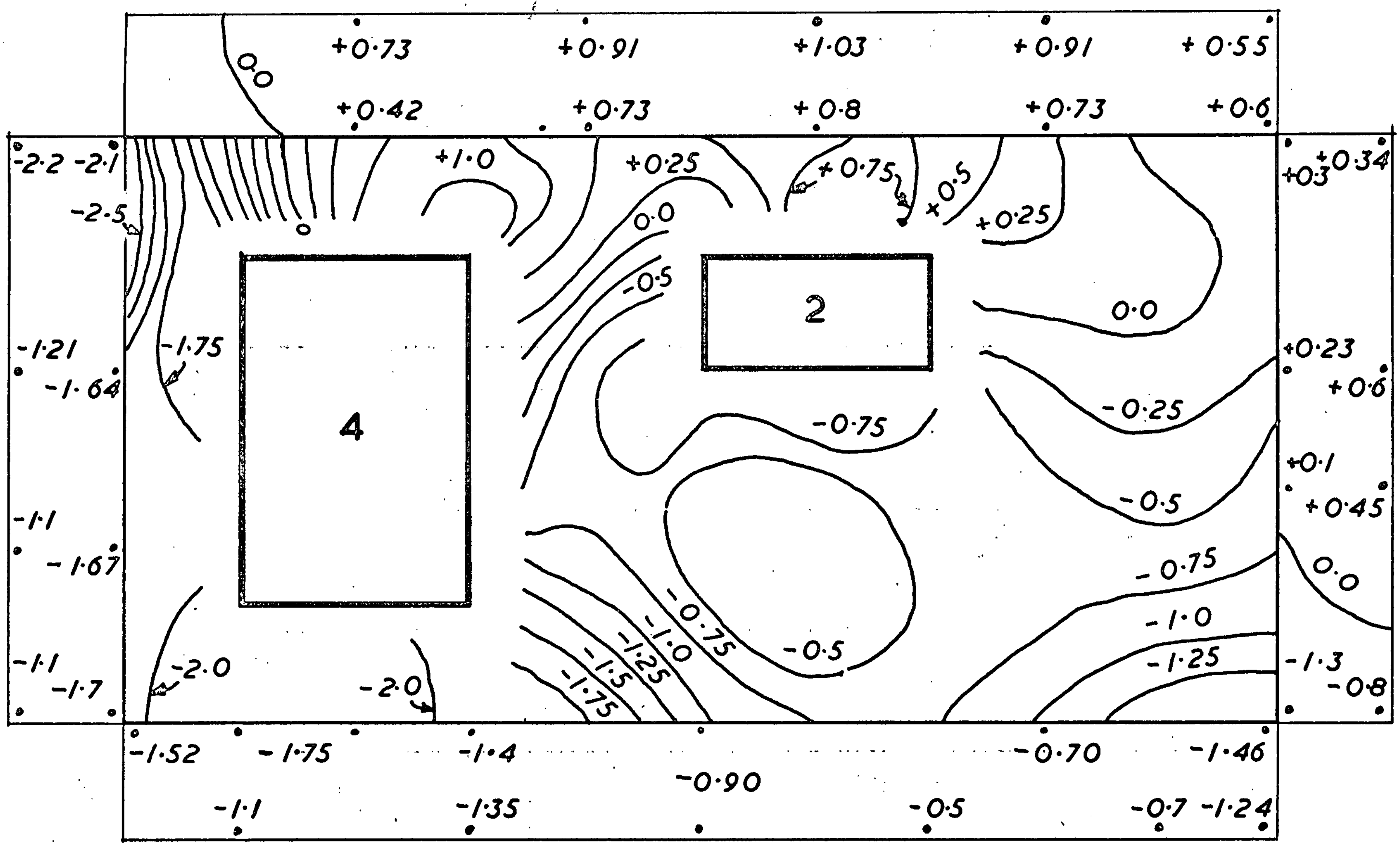


FIG 42 PRESSURE PATTERN GEOM 11 WIND

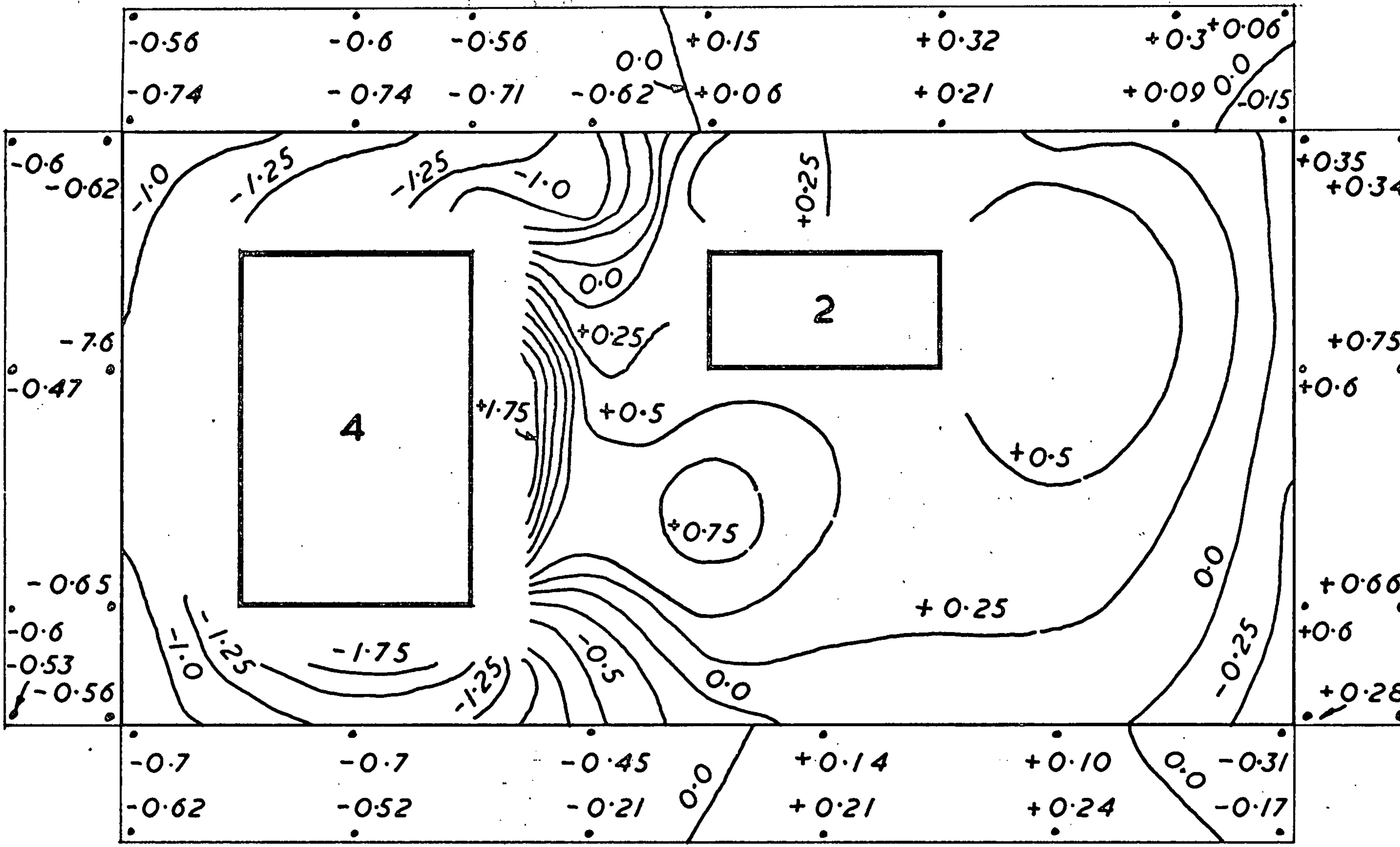


FIG 43 PRESSURE PATTERN GEOM II ← WIND

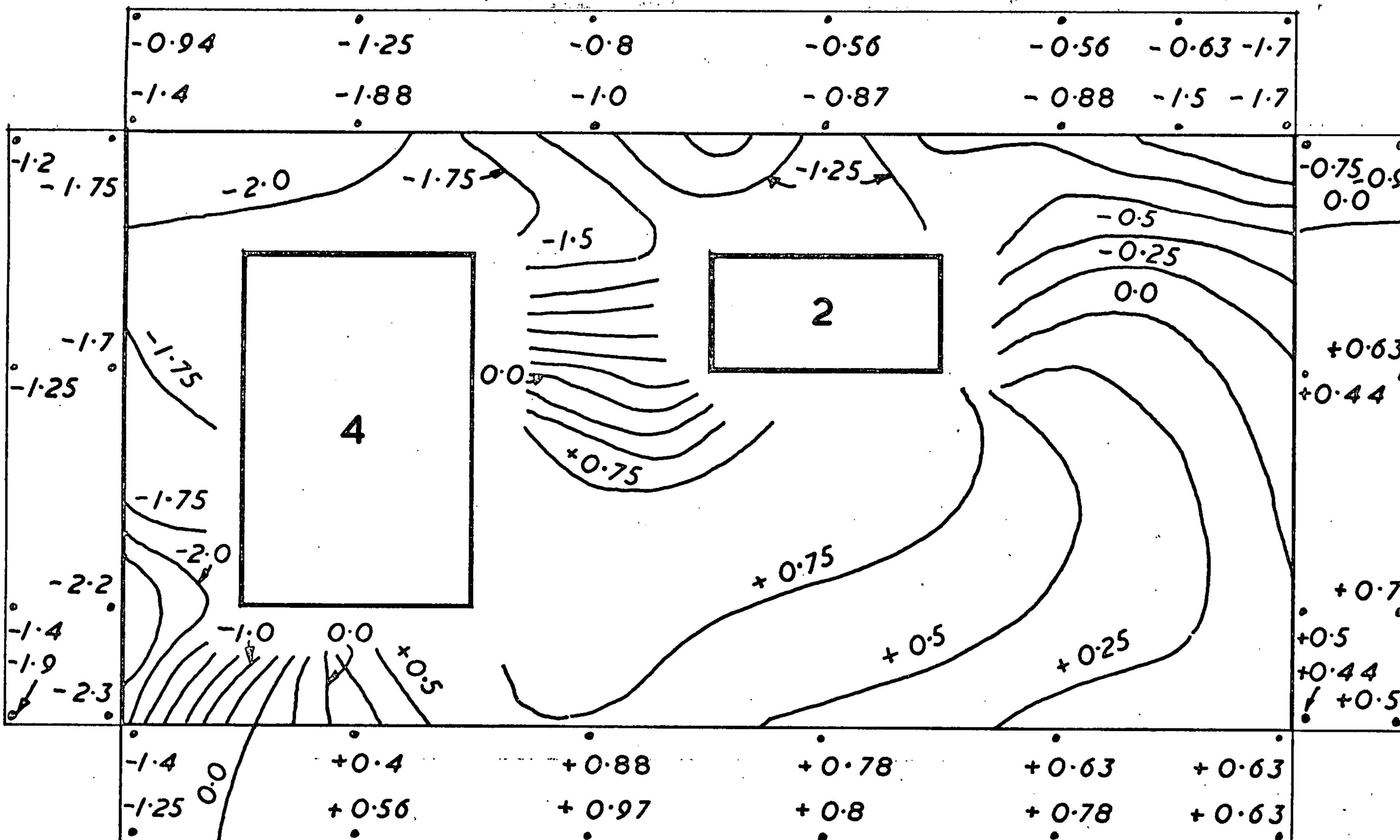


FIG 44 PRESSURE PATTERN GEOM II WIND

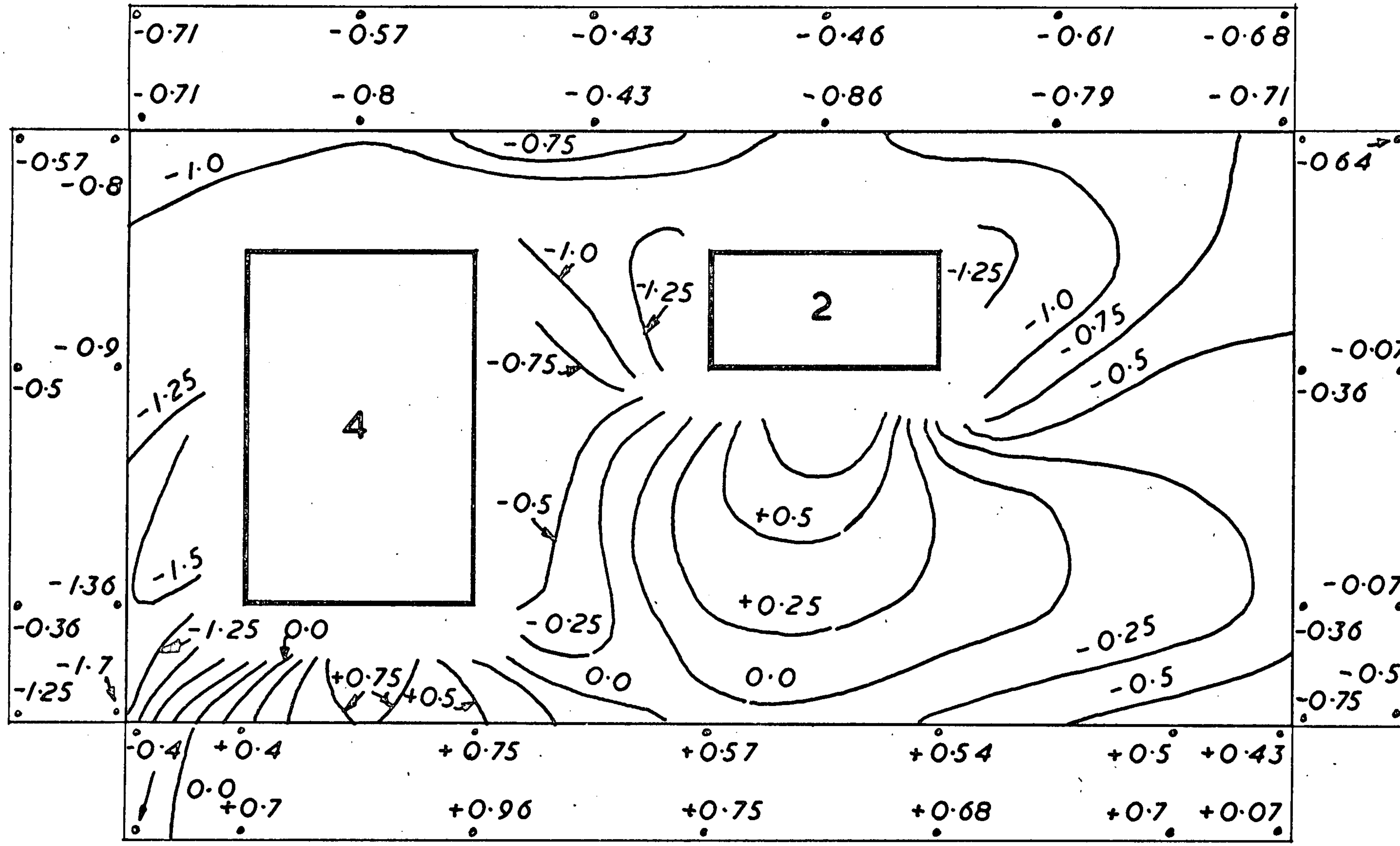


FIG 45 PRESSURE PATTERN GEOM II WIND

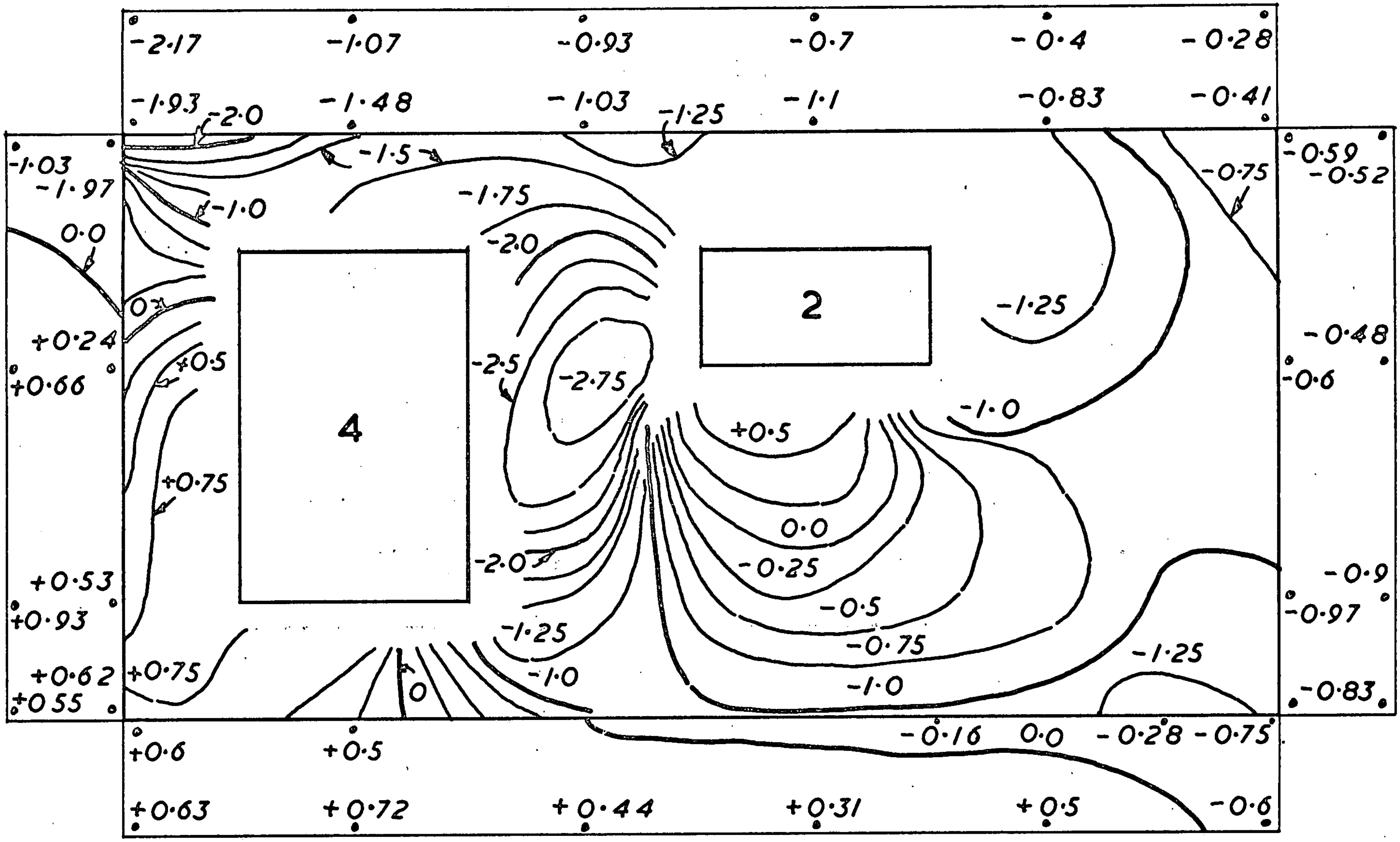


FIG 46 PRESSURE PATTERN GEOM II ↗ WIND

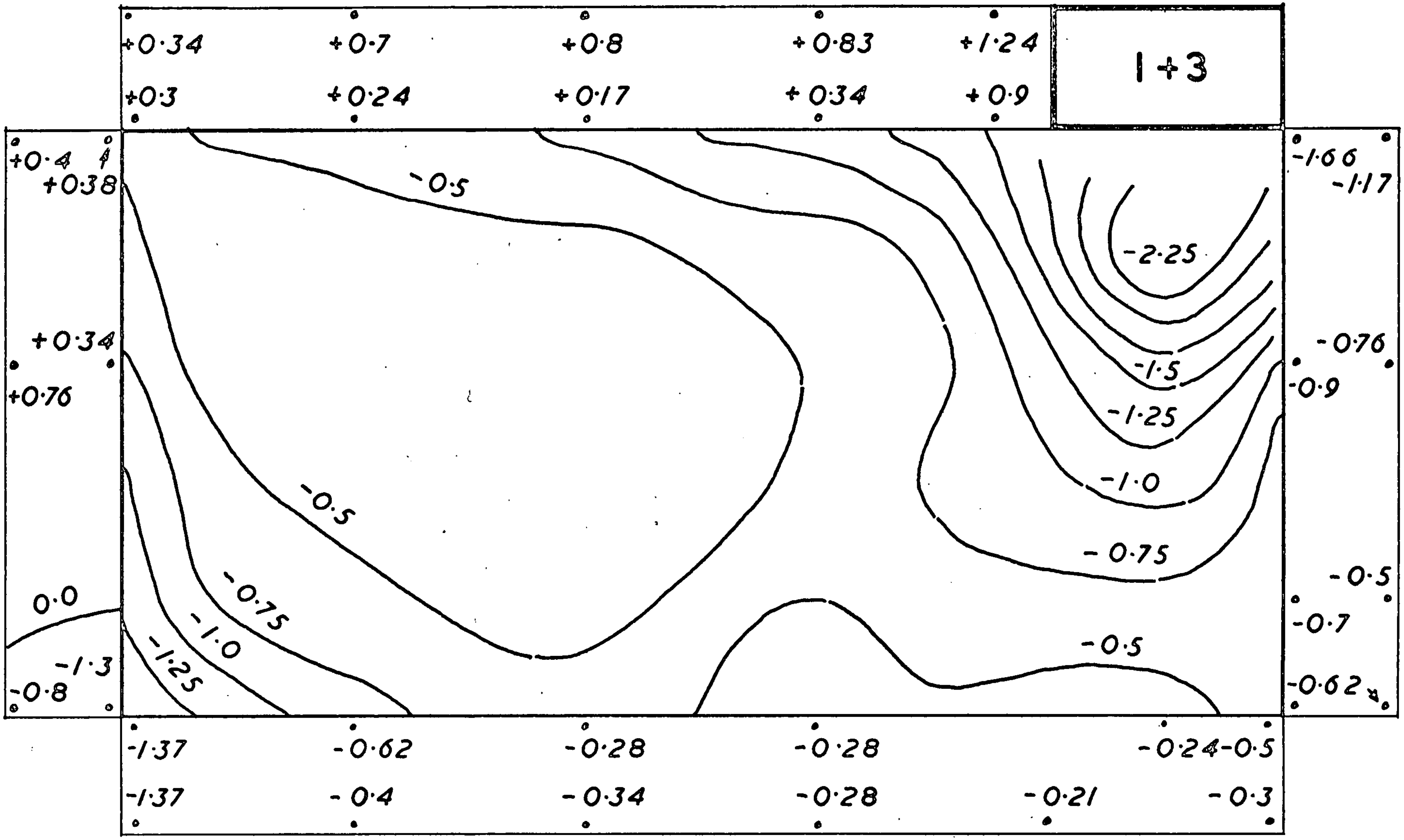


FIG 47 PRESSURE PATTERN GEOM 12 WIND

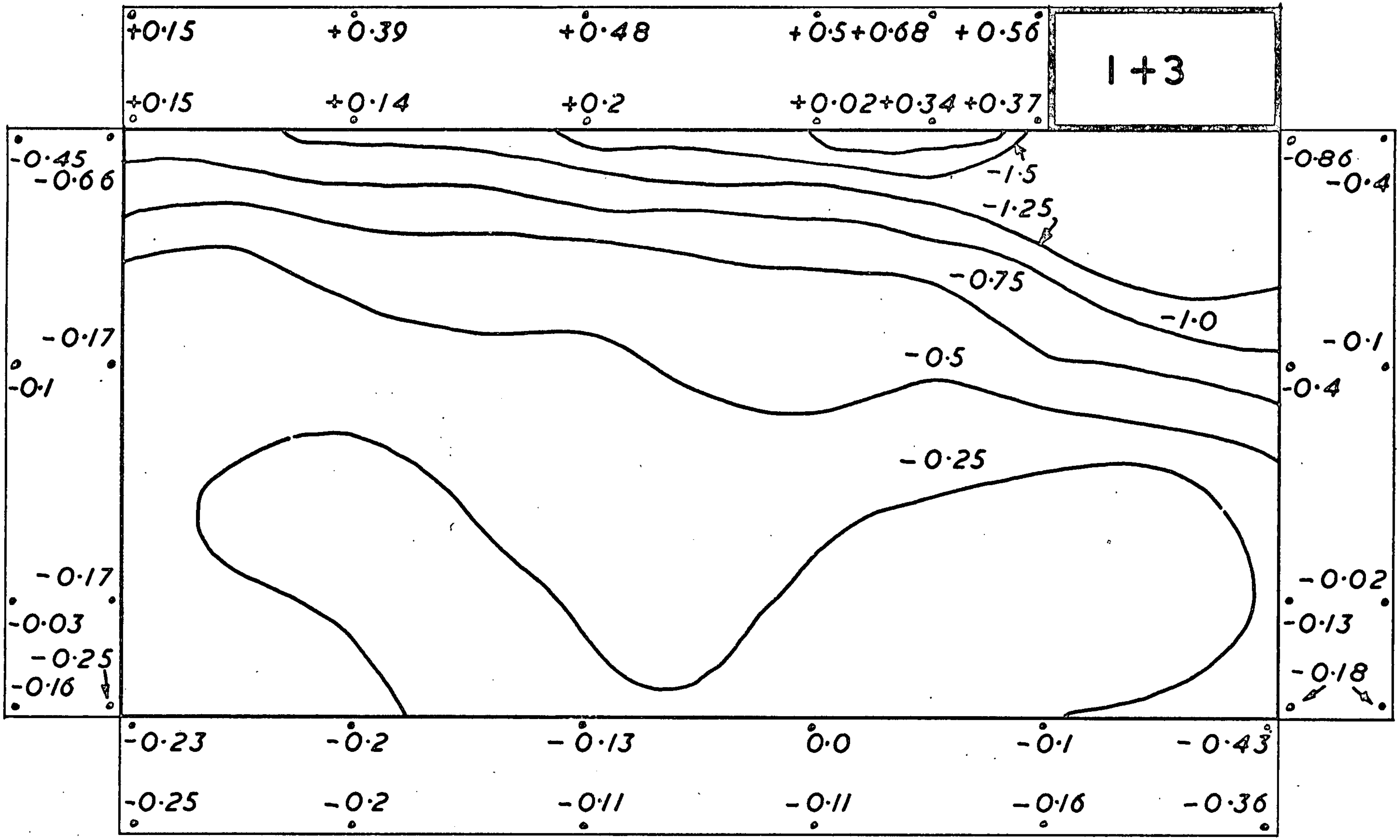


FIG 48 PRESSURE PATTERN GEOM 12 ↓ WIND

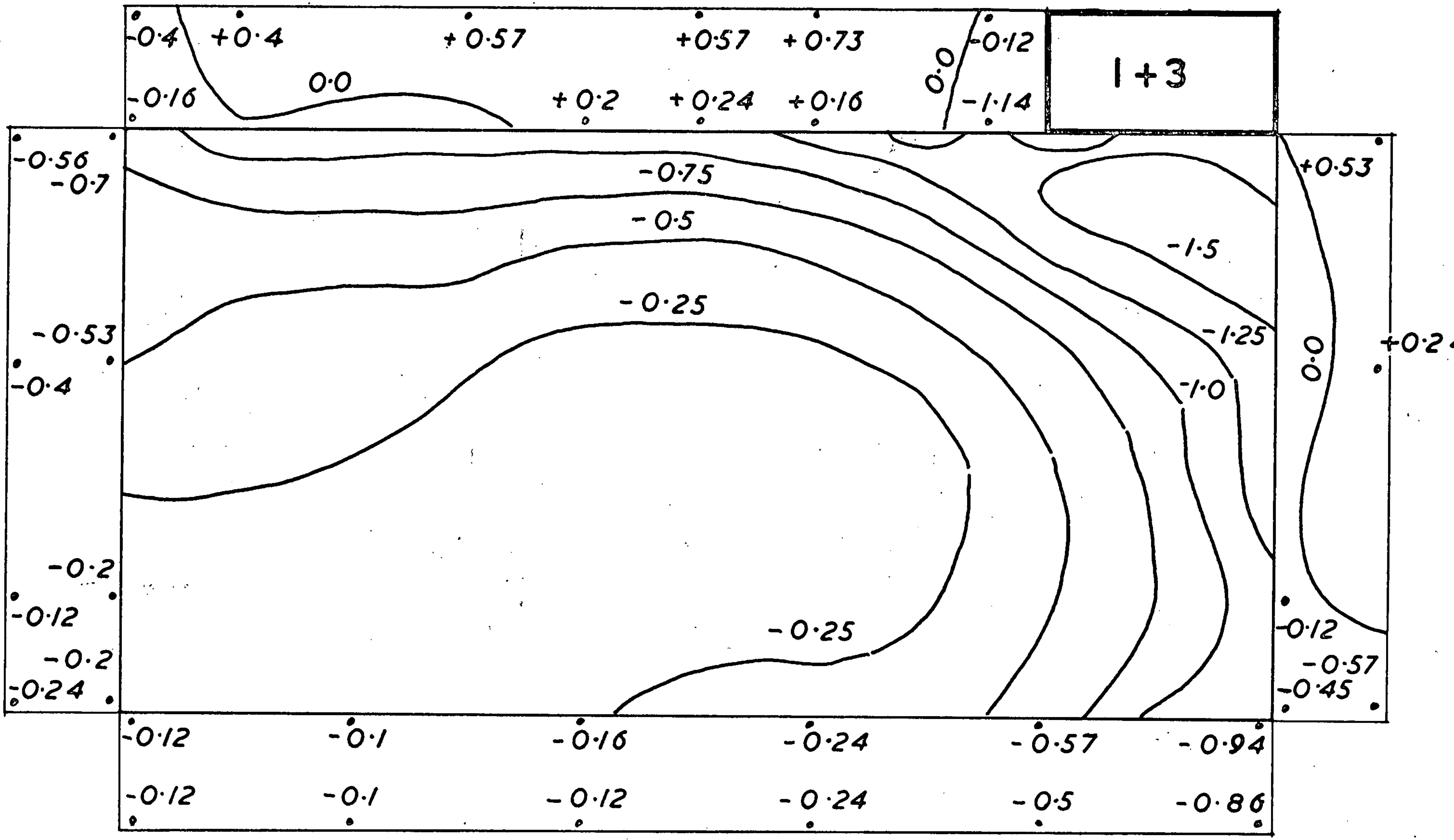


FIG 49 PRESSURE PATTERN GEOM 12 WIND

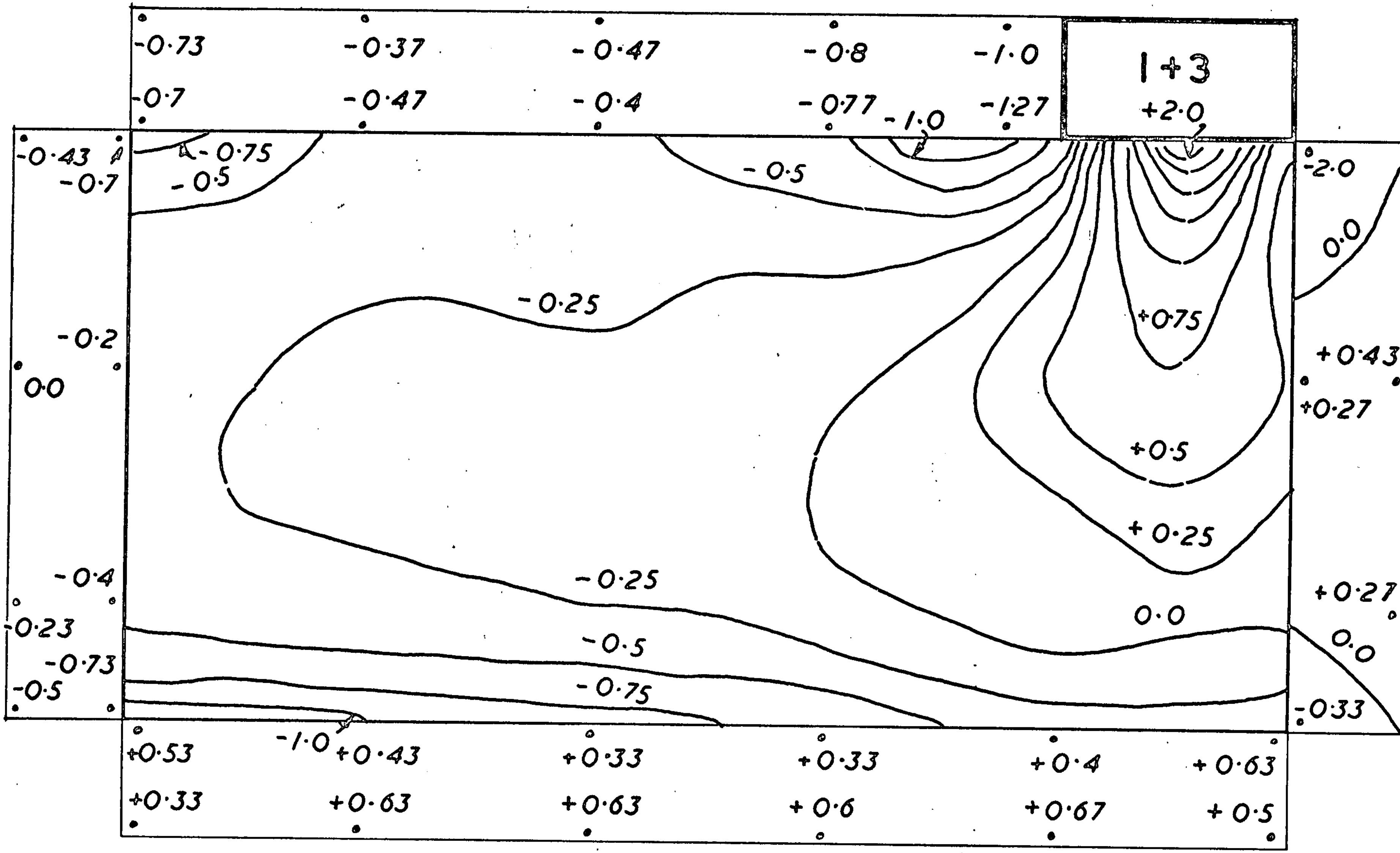


FIG 50 PRESSURE PATTERN GEOM 12 ↑ WIND

1 + 3

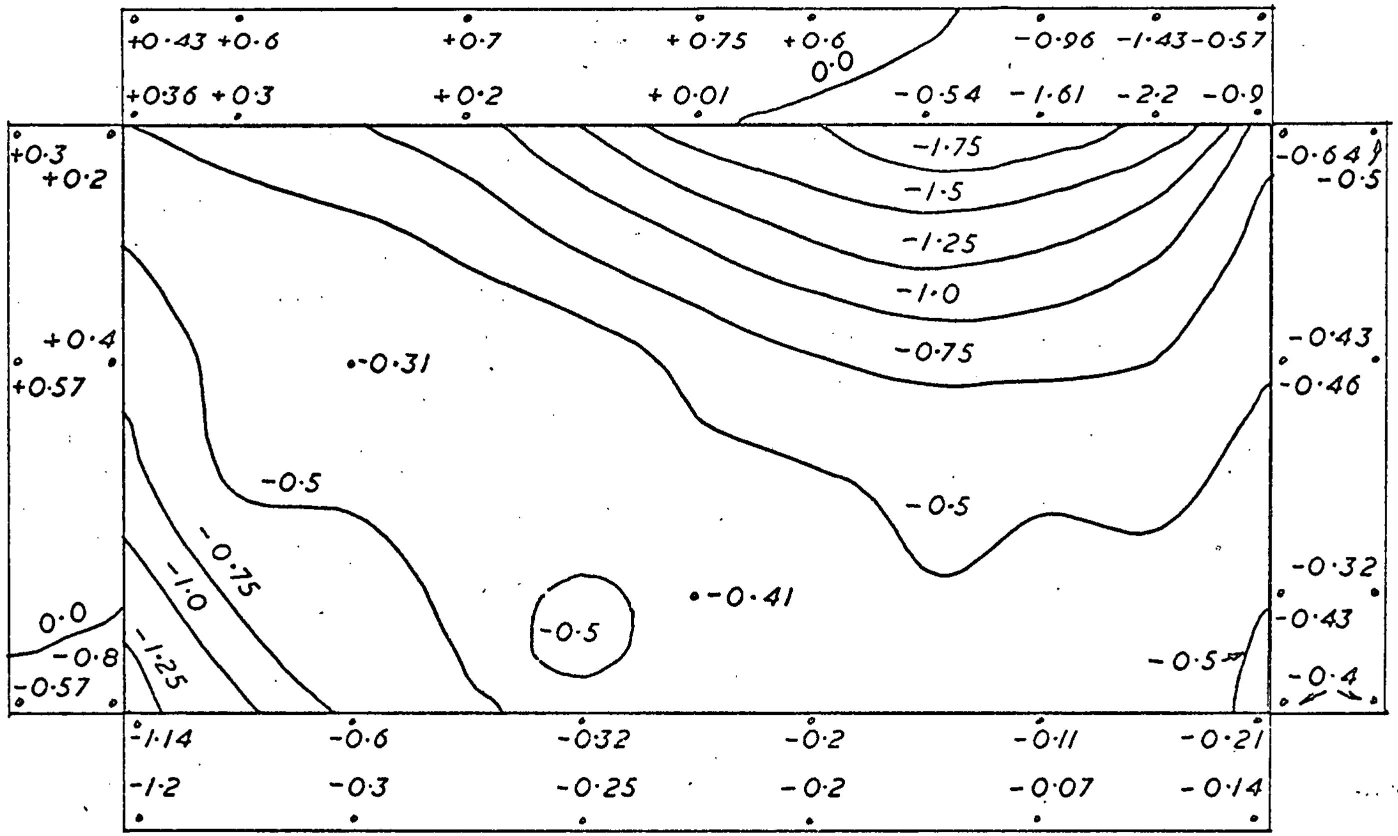


FIG 51 PRESSURE PATTERN GEOM 13 ↘ WIND

1 +3

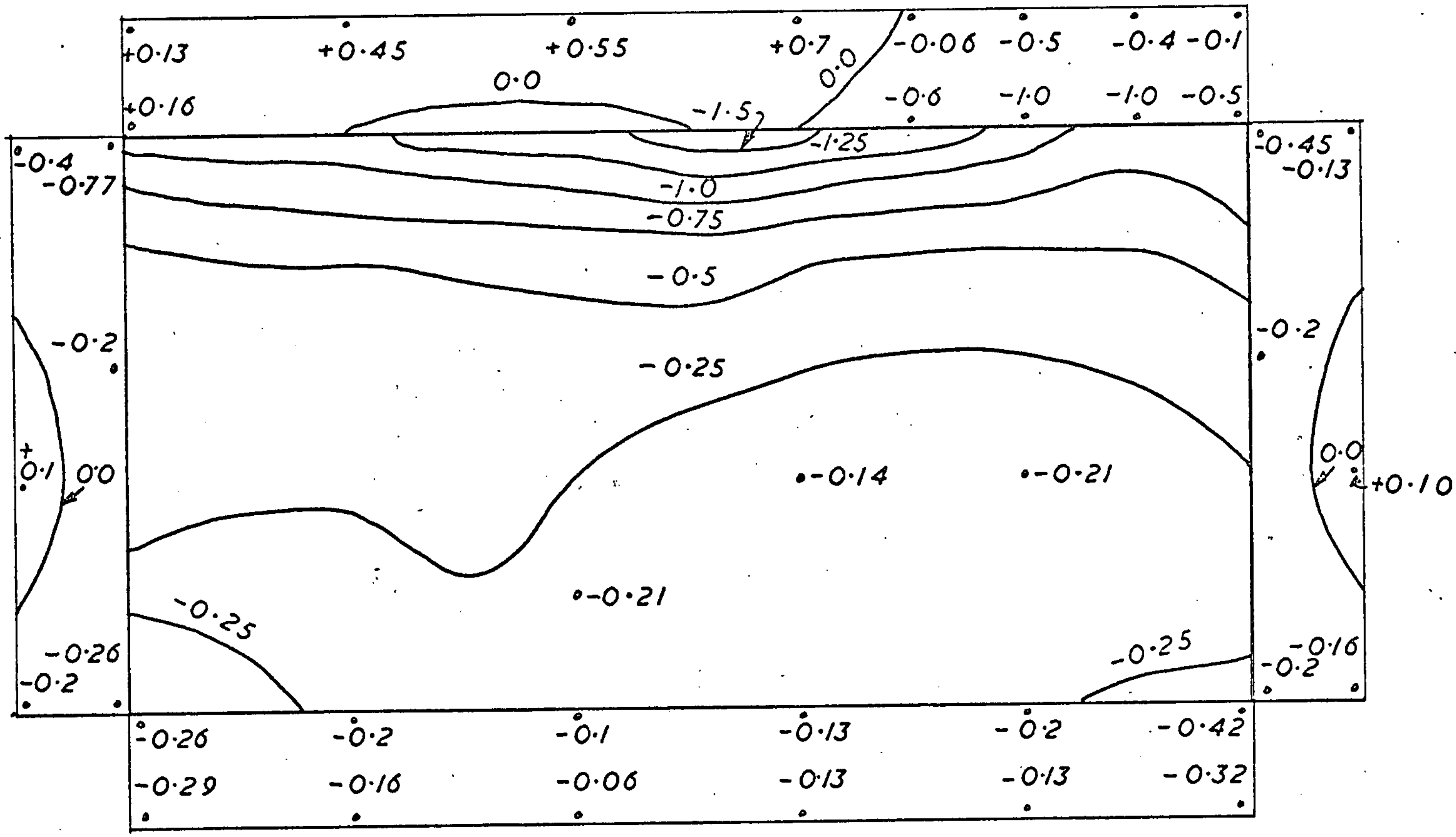


FIG 52 PRESSURE PATTERN GEOM 13 ↓ WIND

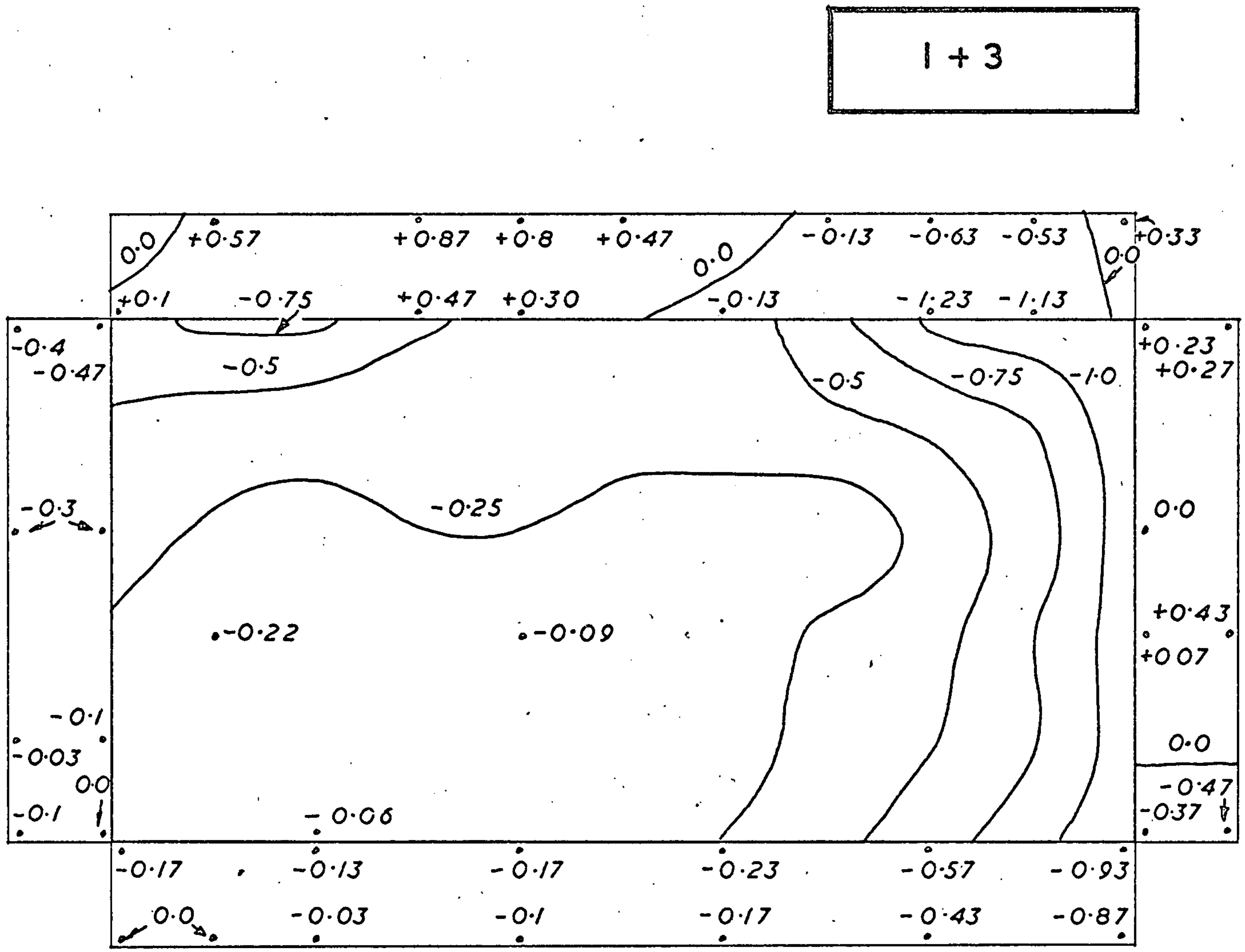


FIG 53 PRESSURE PATTERN GEOM 13 ↙ WIND

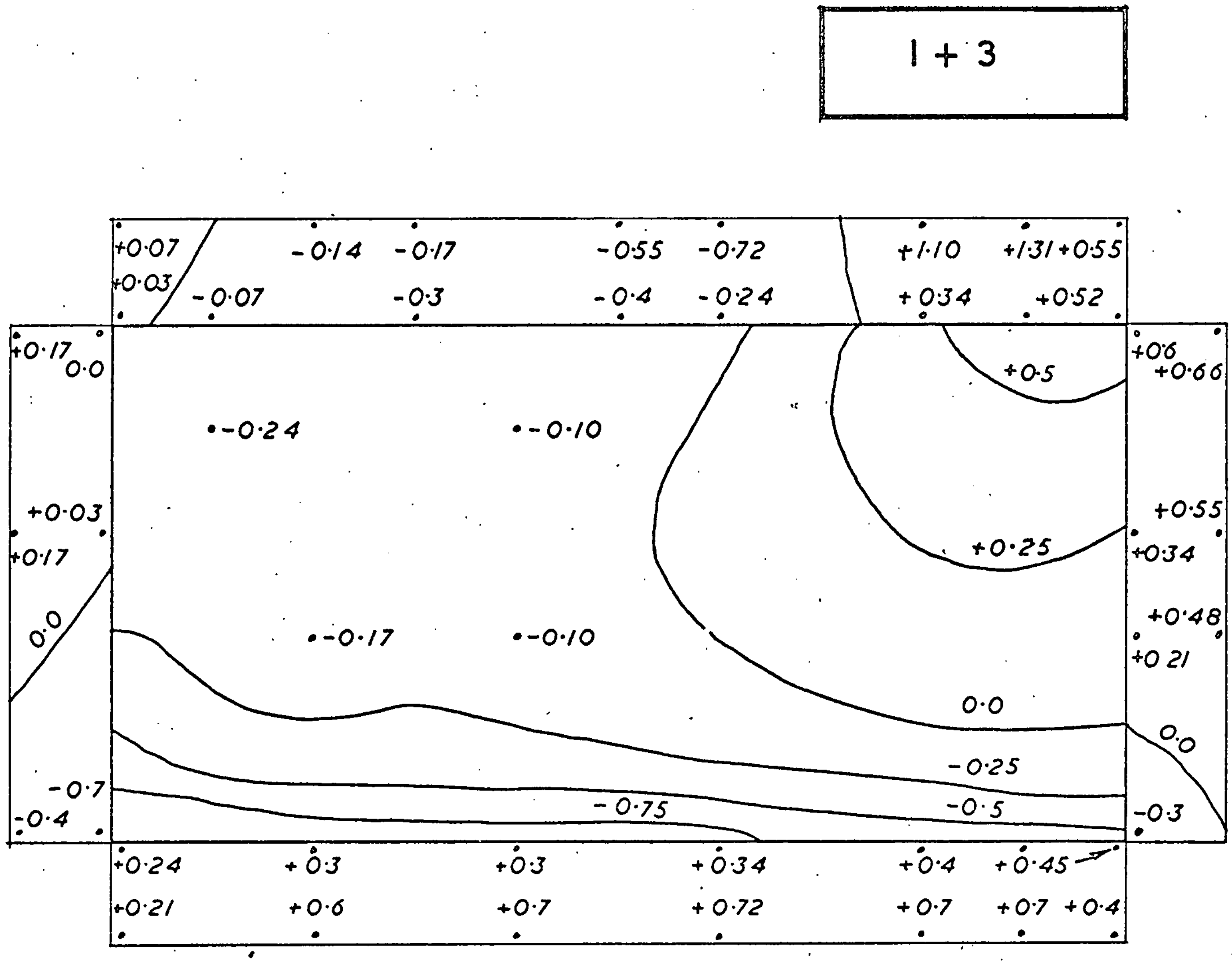


FIG 54 PRESSURE PATTERN GEOM 13 ↑ WIND

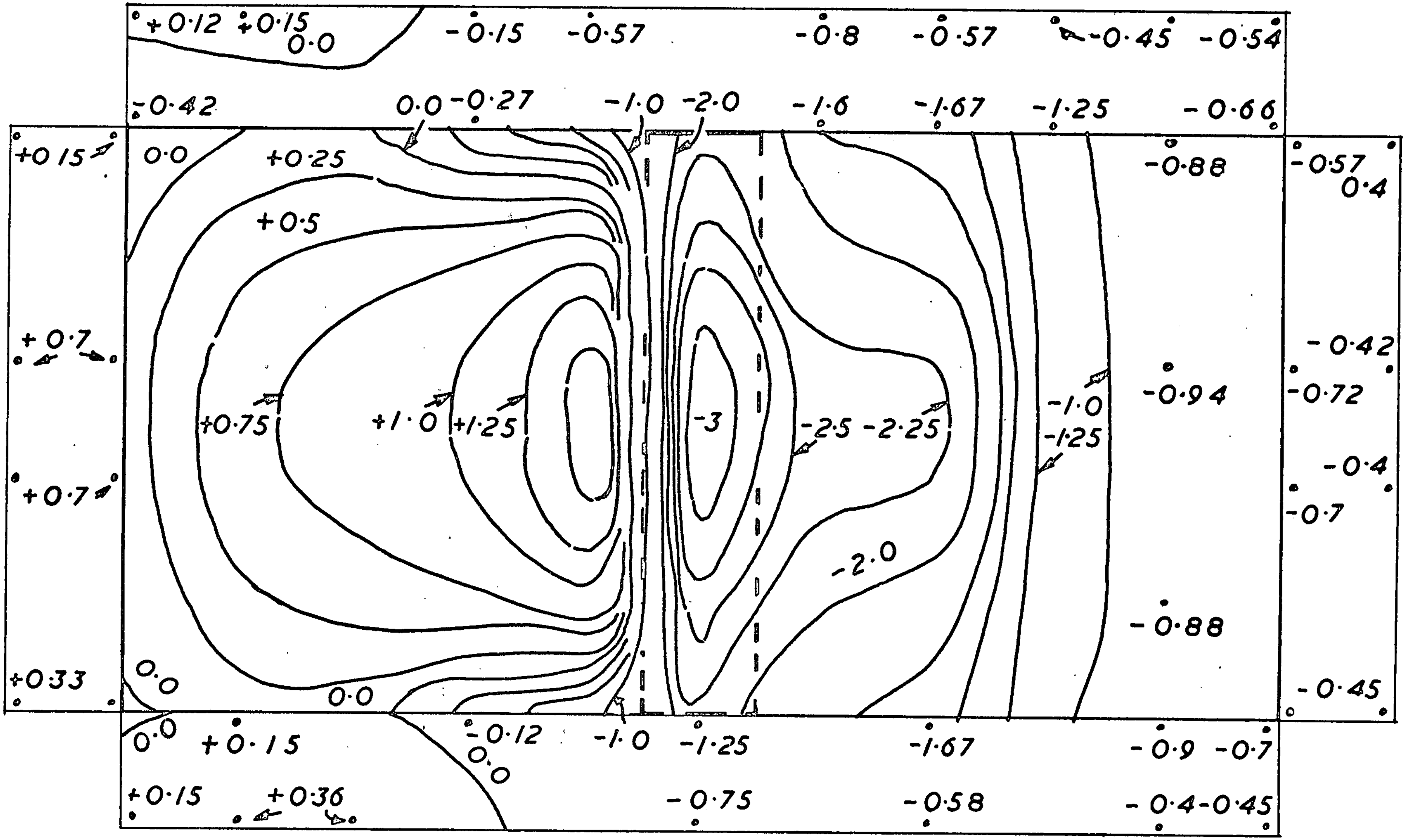


FIG 55 PRESSURE PATTERN GEOM 14 → WIND

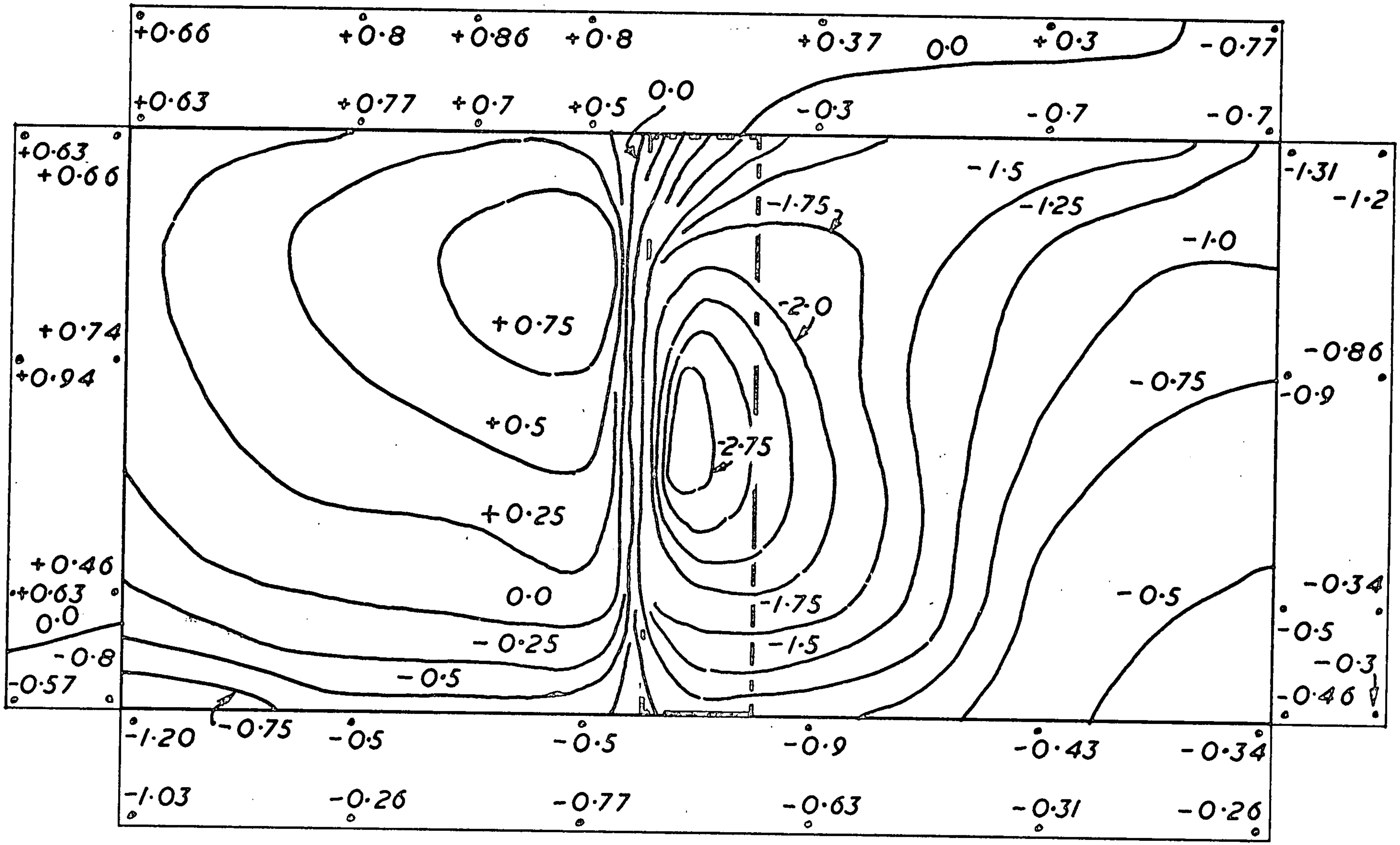


FIG 56 PRESSURE PATTERN GEOM 14 ↘ WIND

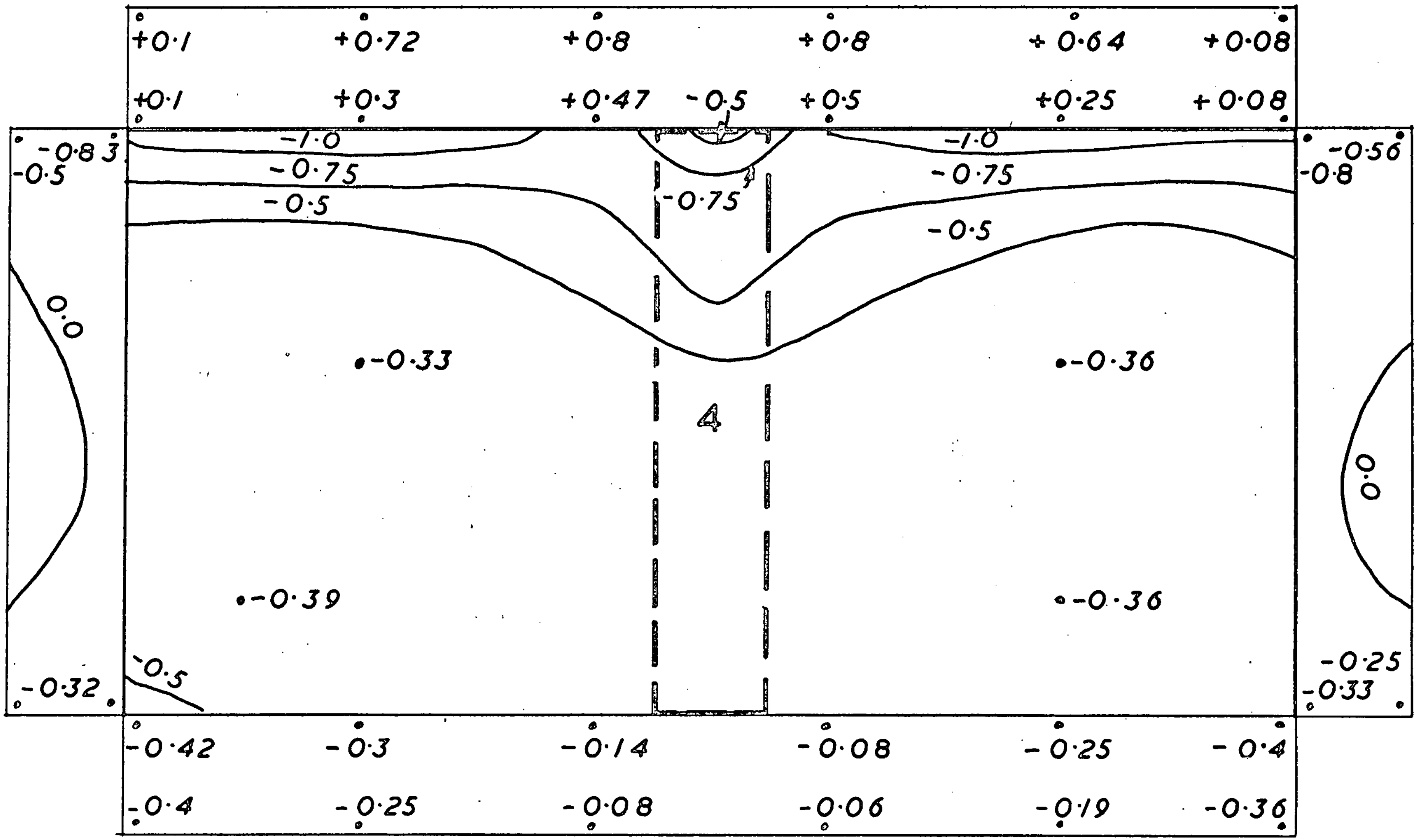


FIG 57 PRESSURE PATTERN GEOM 14 ↓ WIND

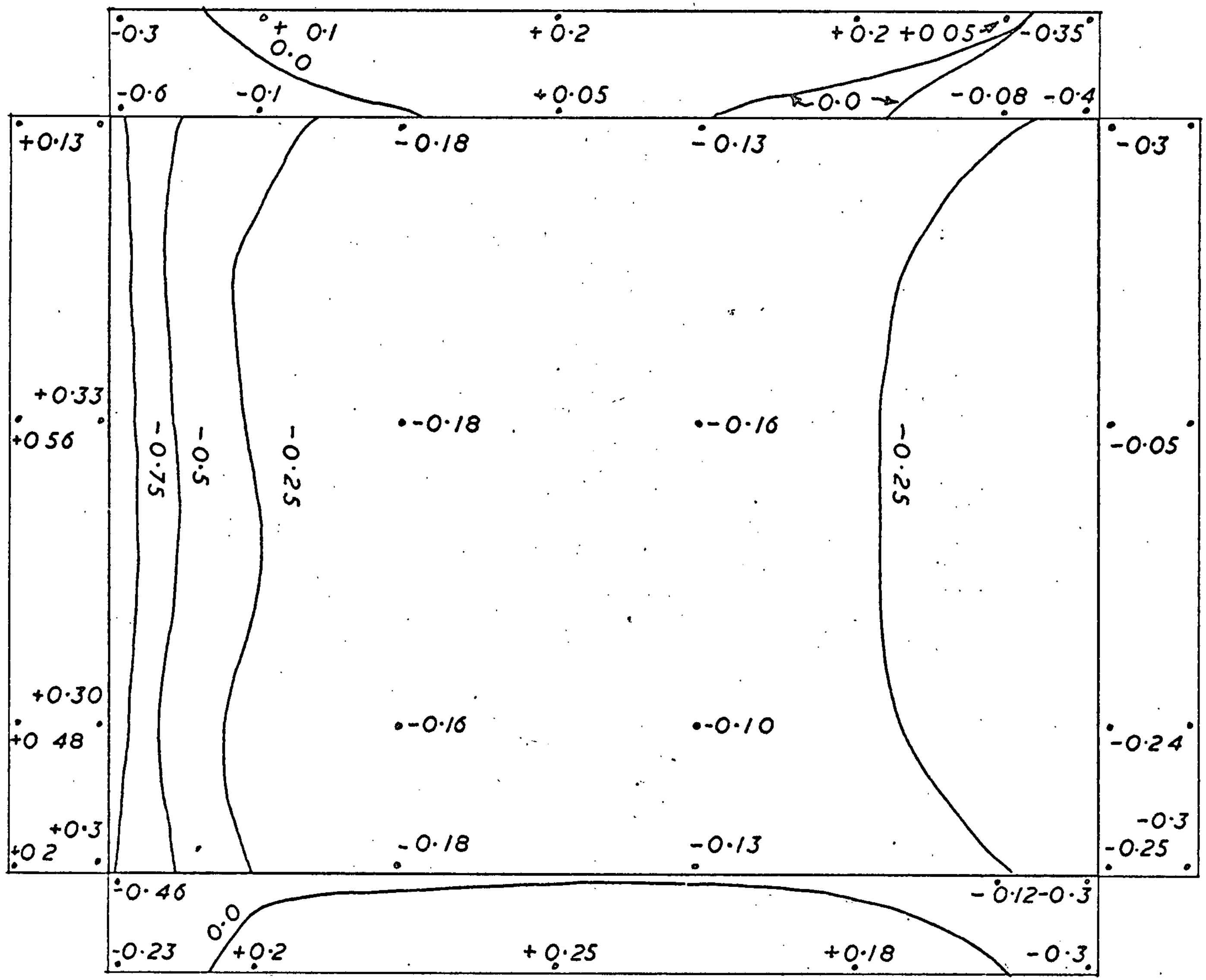


FIG 58 PRESSURE PATTERN GEOM 15 → WIND

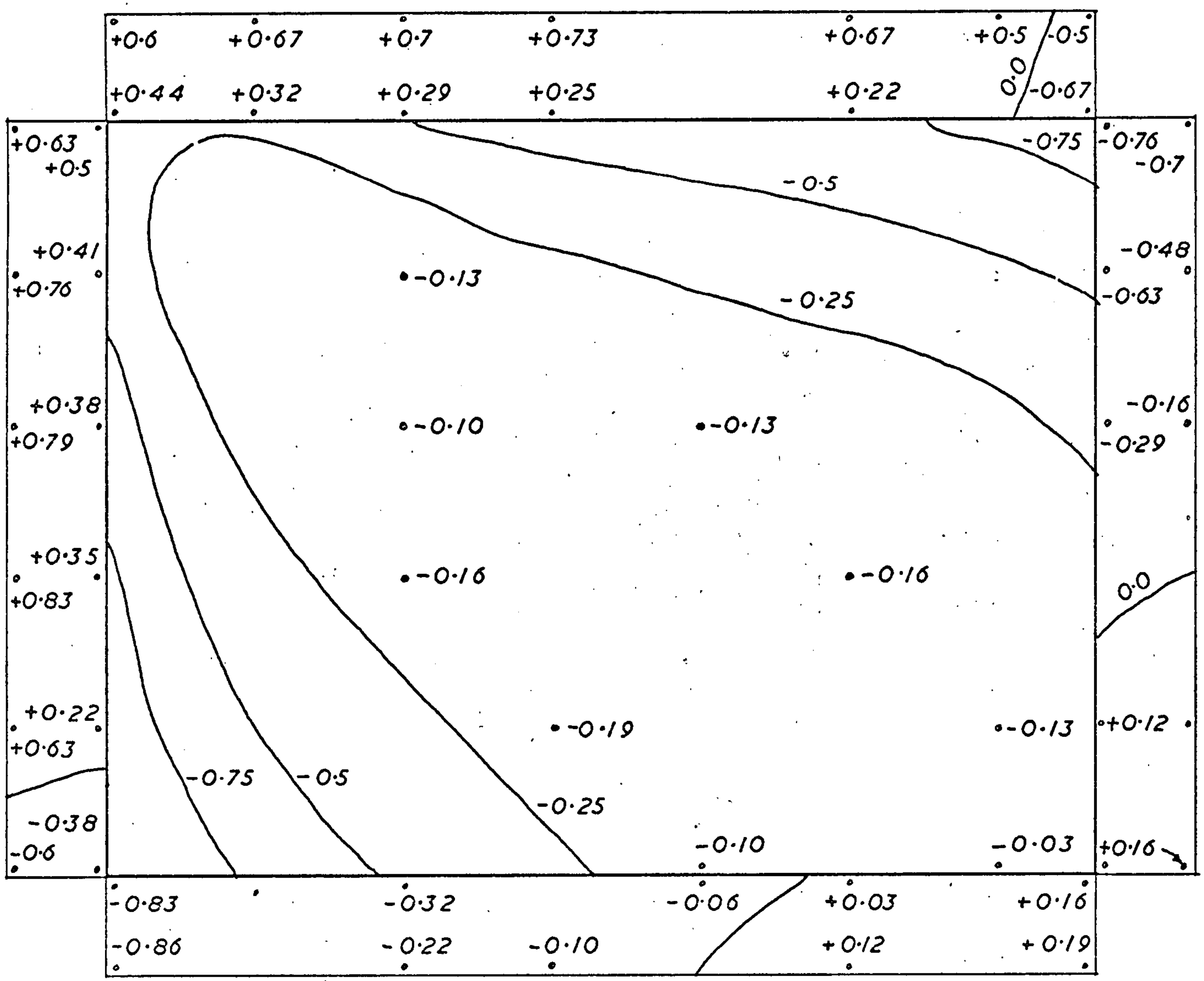


FIG 59 PRESSURE PATTERN GEOM 15 ↘ WIND

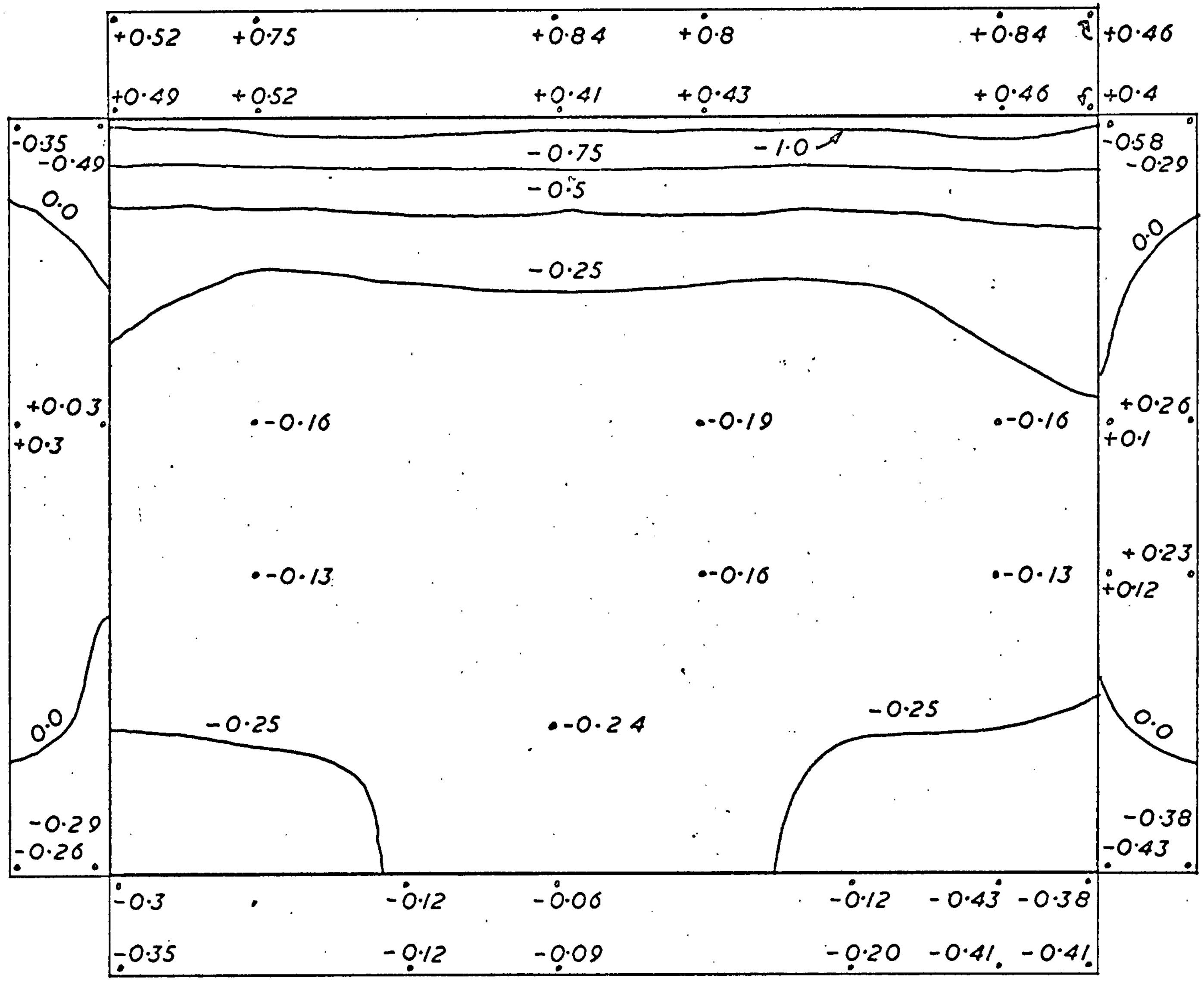


FIG 60 PRESSURE PATTERN GEOM 15 ↓ WIND

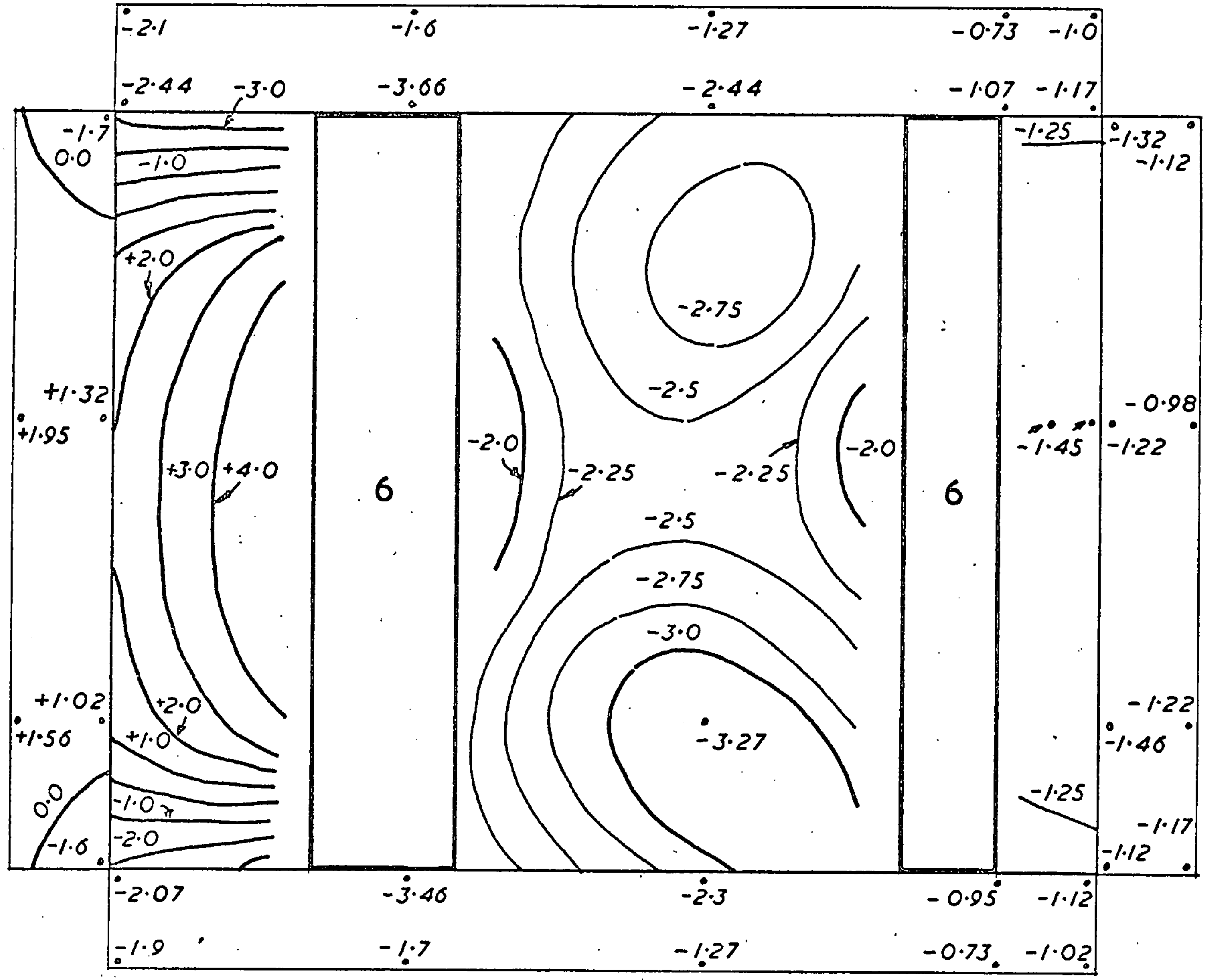


FIG 61 PRESSURE PATTERN GEOM 16 → WIND

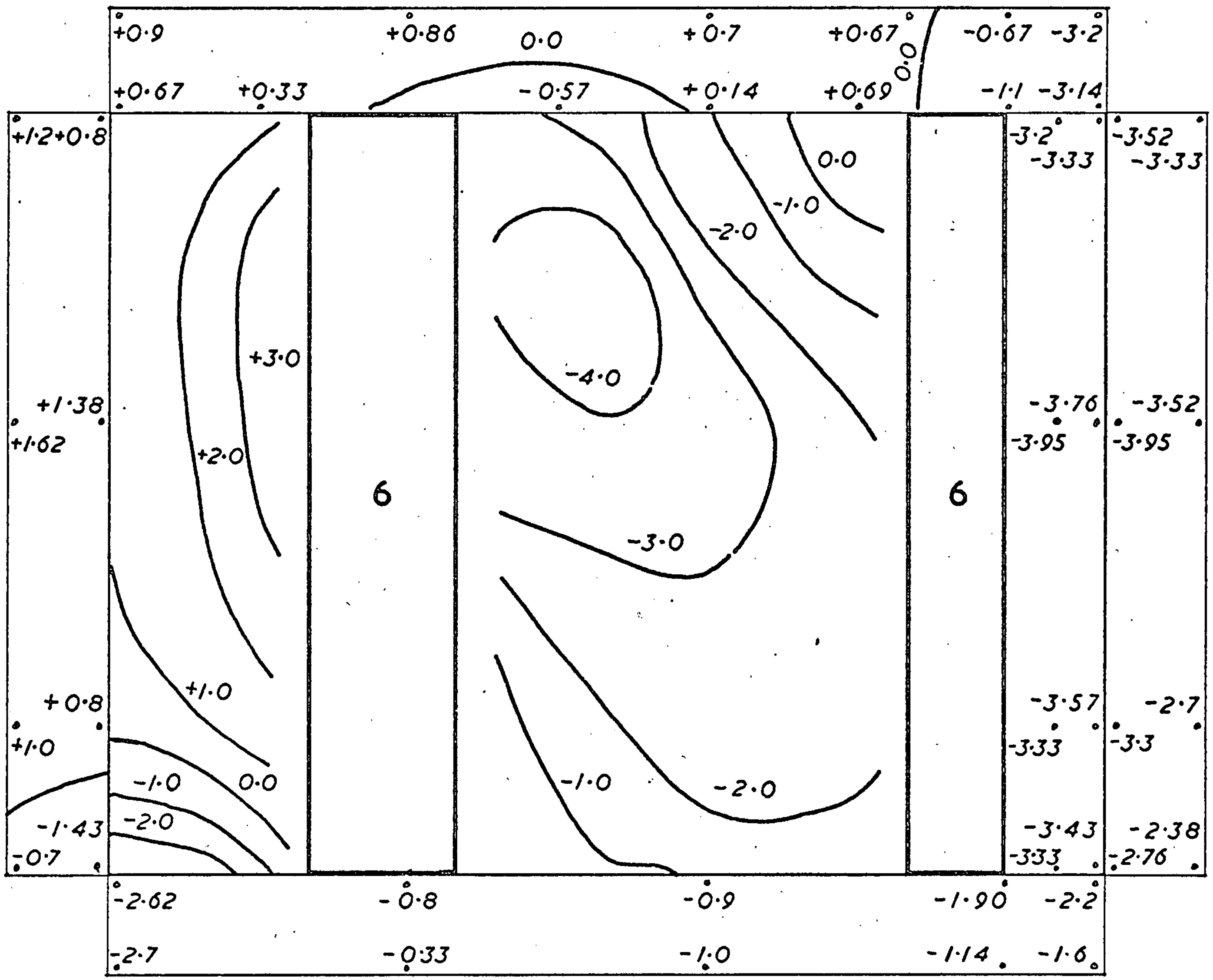


FIG 62 PRESSURE PATTERN GEOM 16 ↘ WIND

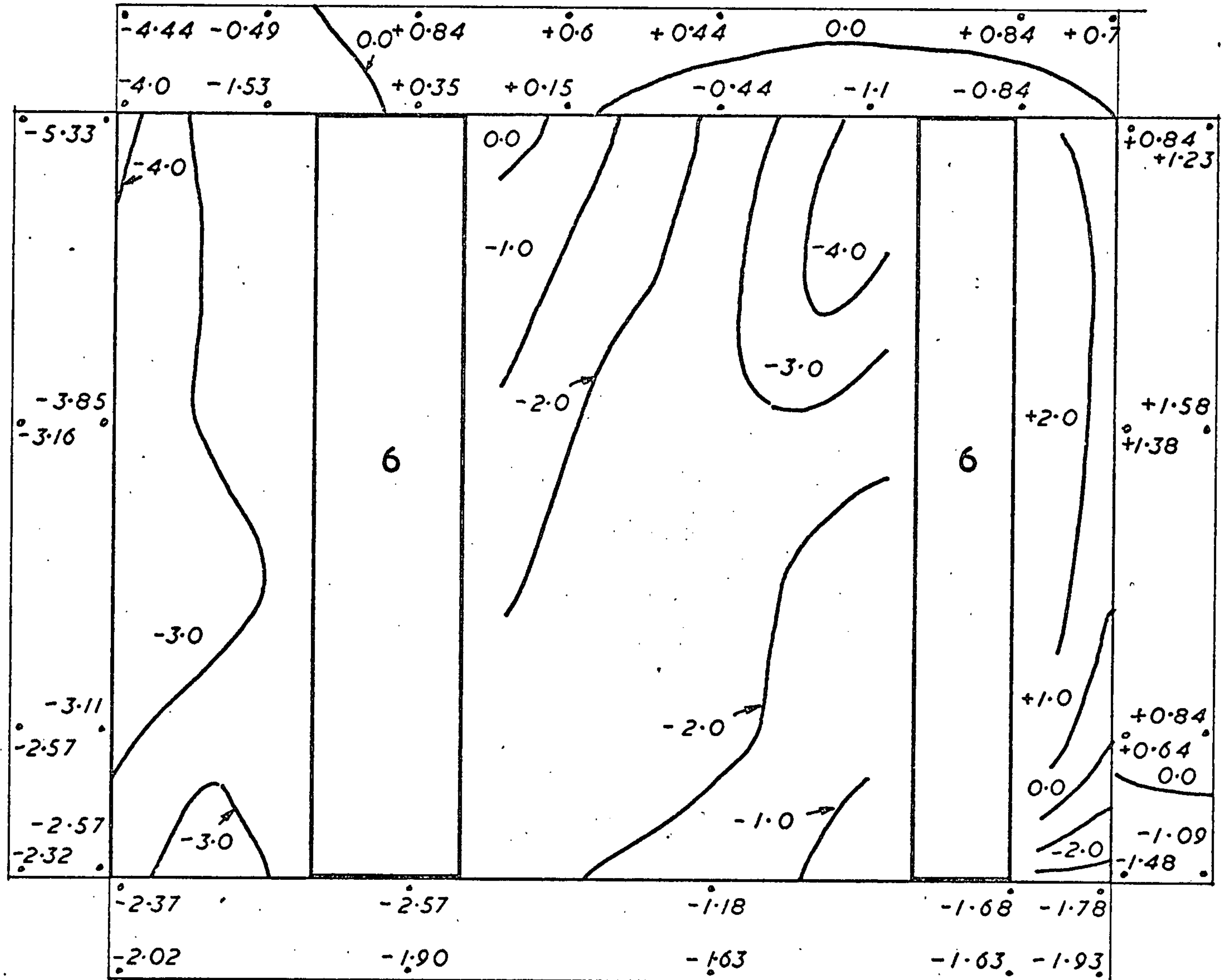


FIG 63 PRESSURE PATTERN GEOM 16 ↙ WIND

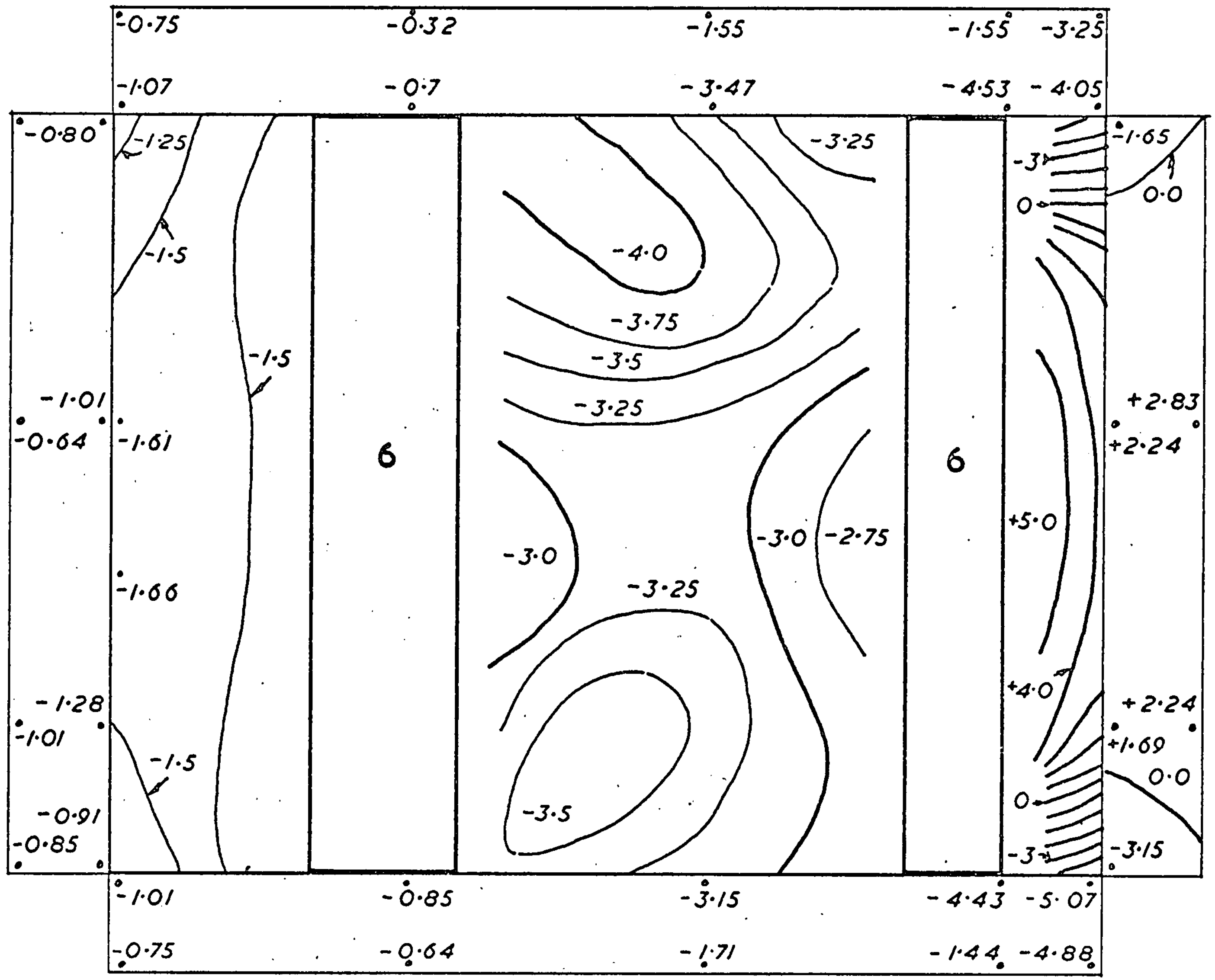


FIG 64 PRESSURE PATTERN GEOM 16 ← WIND

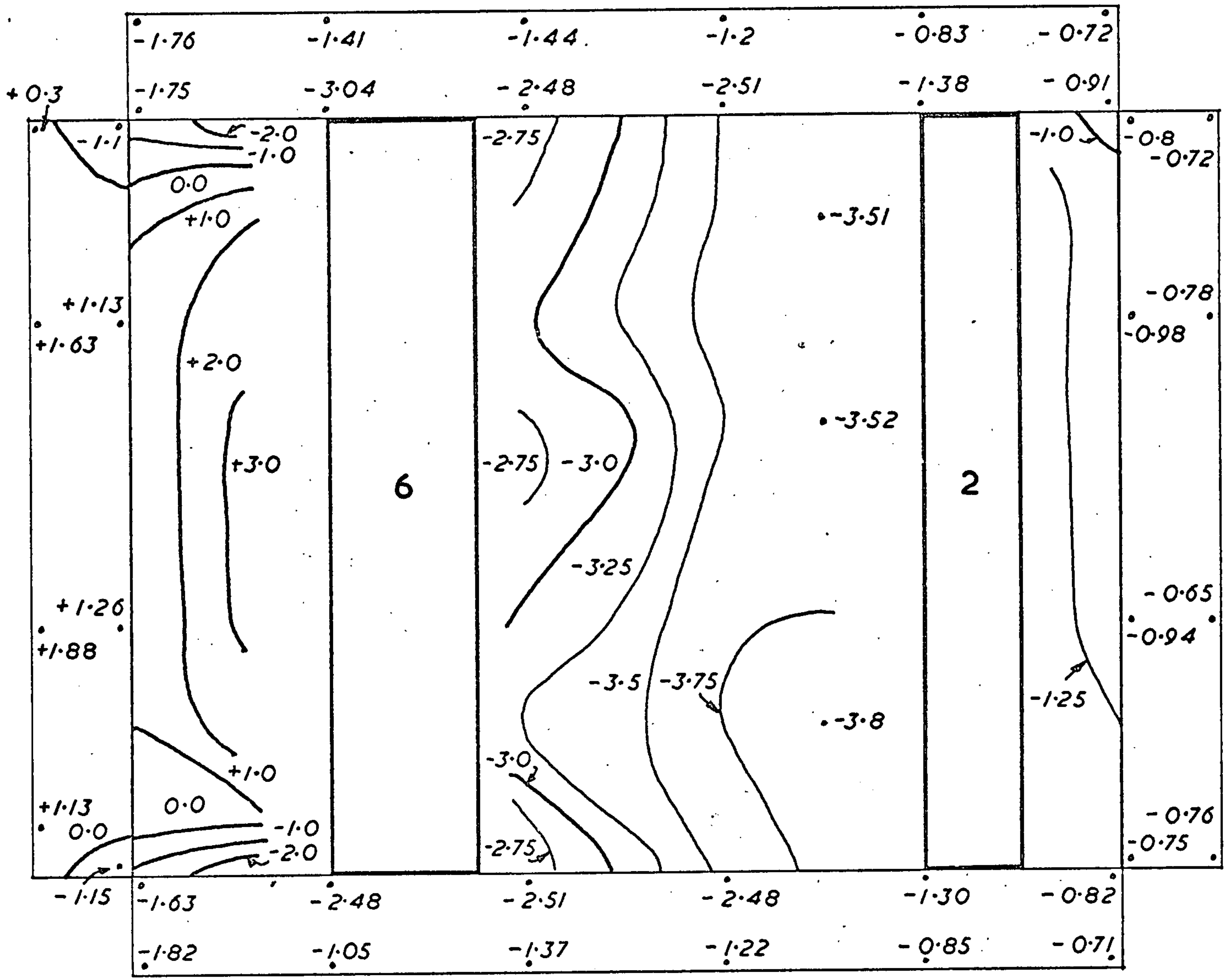


FIG 65 PRESSURE PATTERN GEOM 17 → WIND

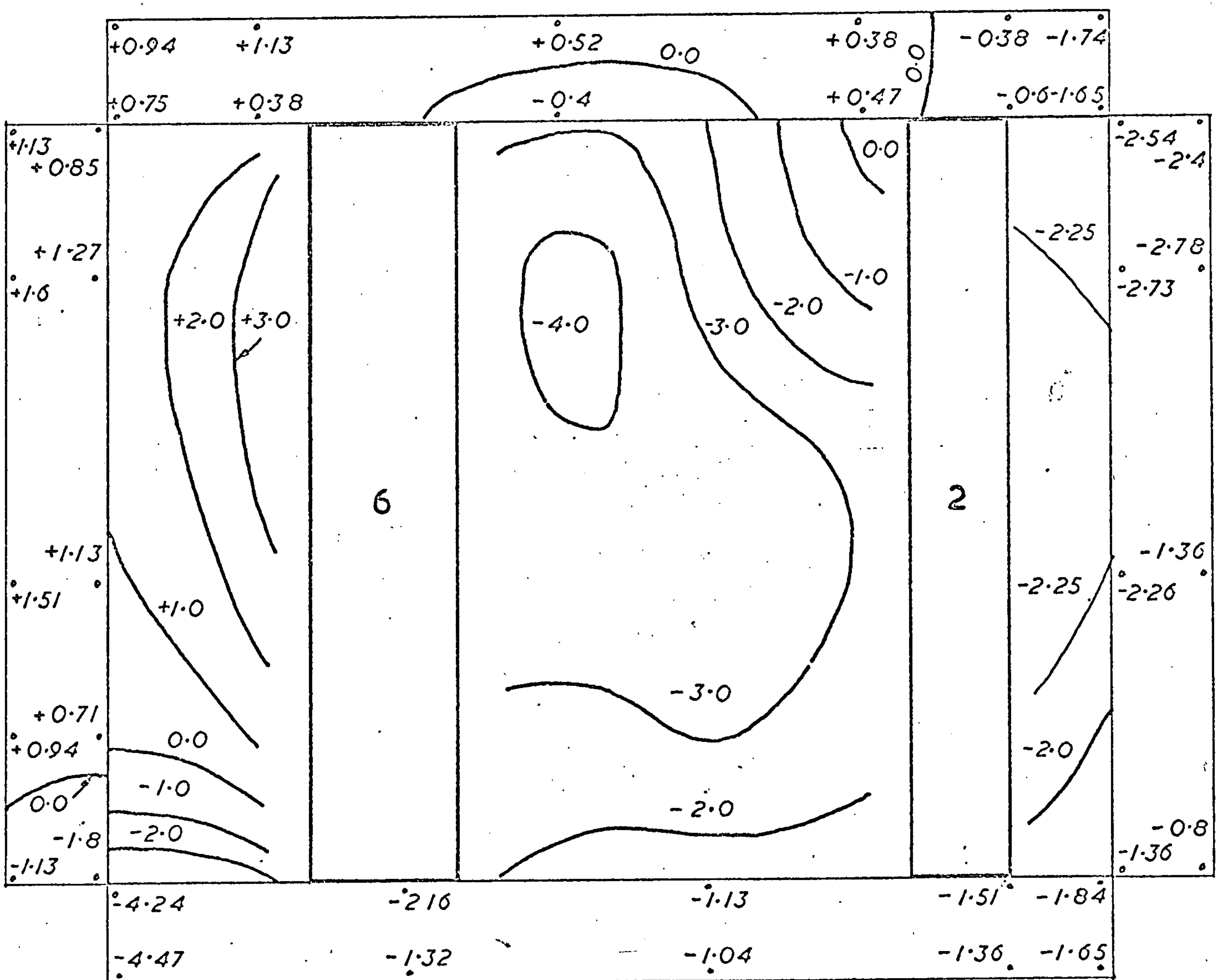


FIG 66 PRESSURE PATTERN GEOM 17 ↘ WIND

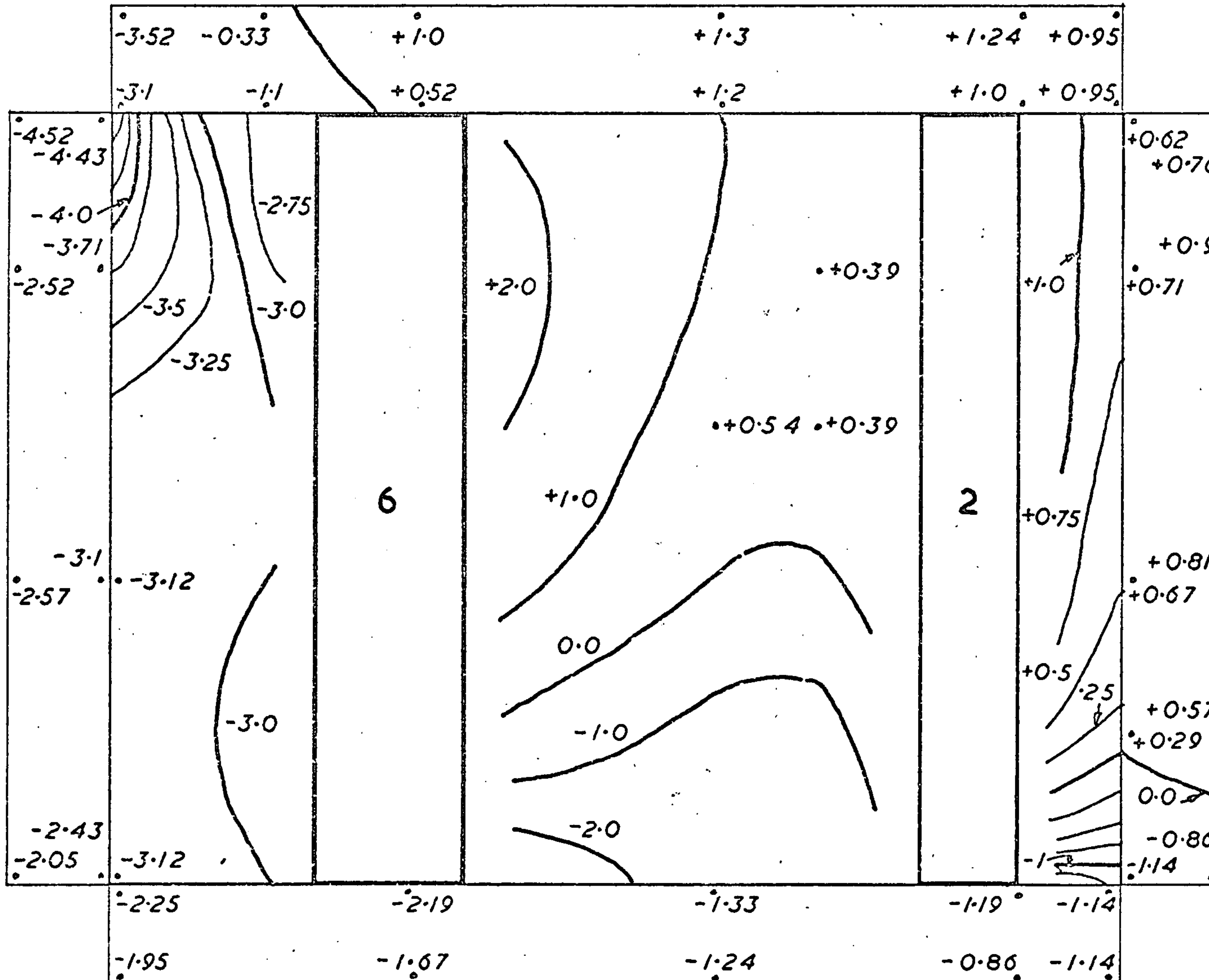


FIG 67 PRESSURE PATTERN GEOM 17 ↙ WIND

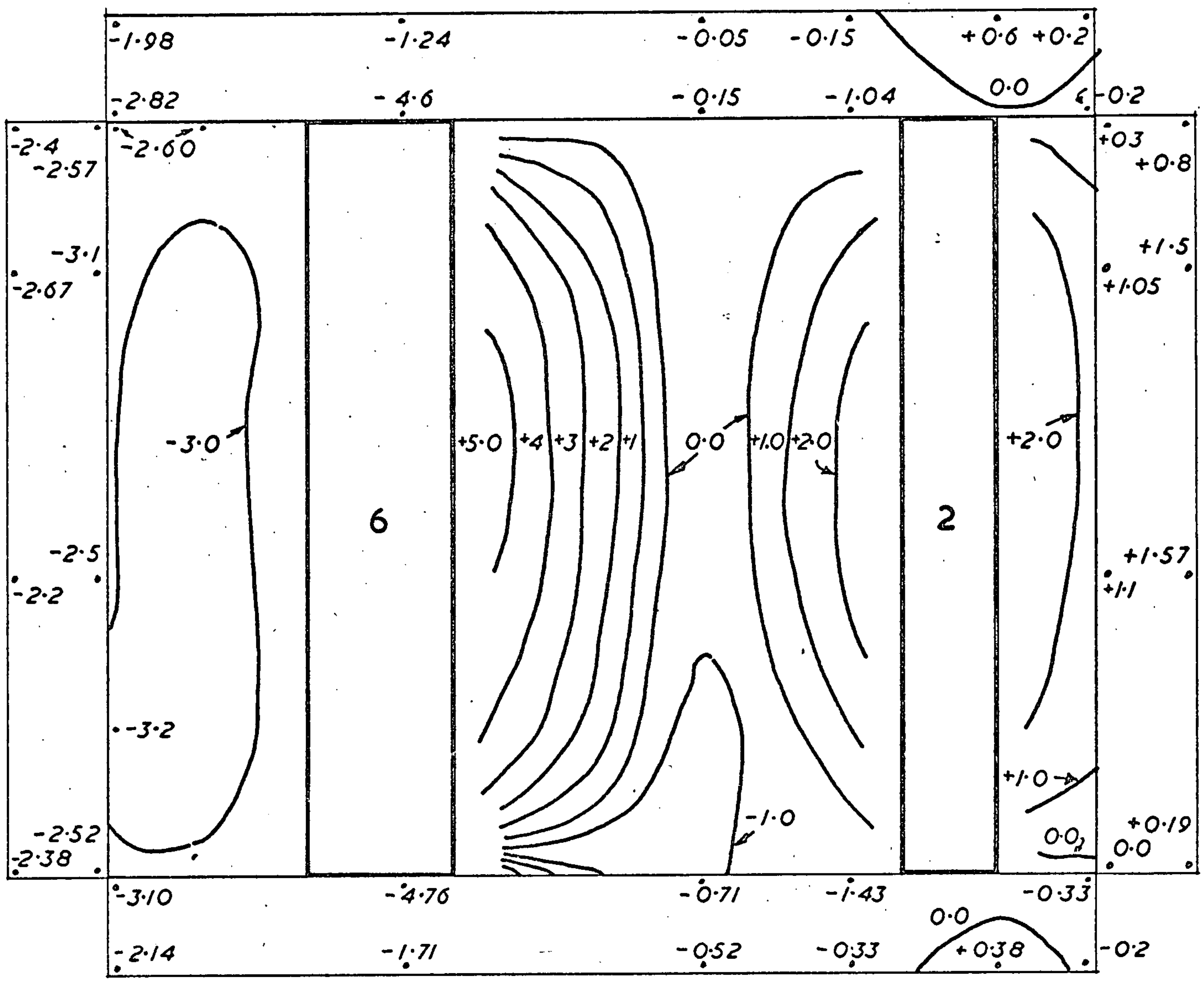


FIG 68 PRESSURE PATTERN GEOM 17 ← WIND

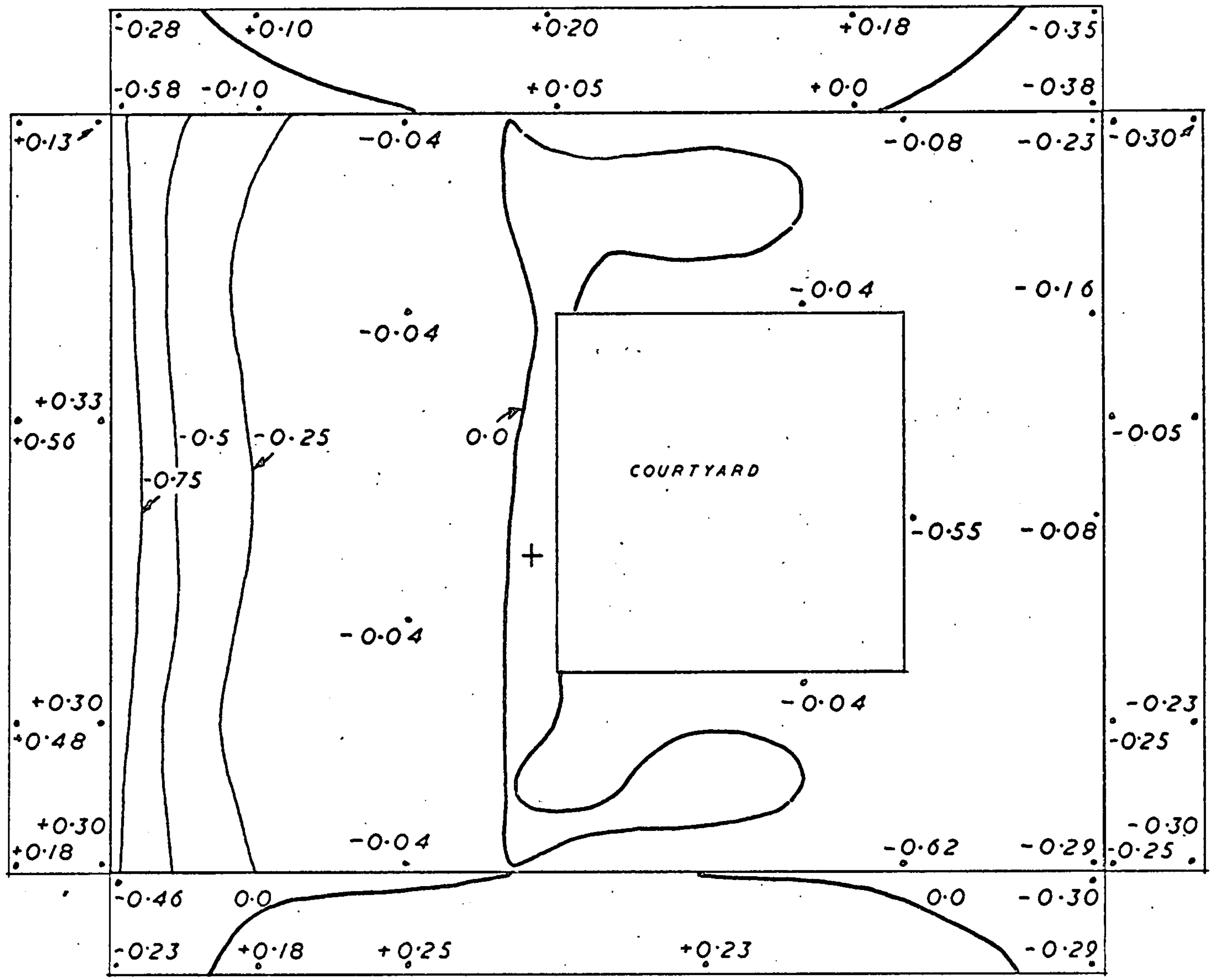


FIG 69A PRESSURE PATTERN GEOM 18 → WIND

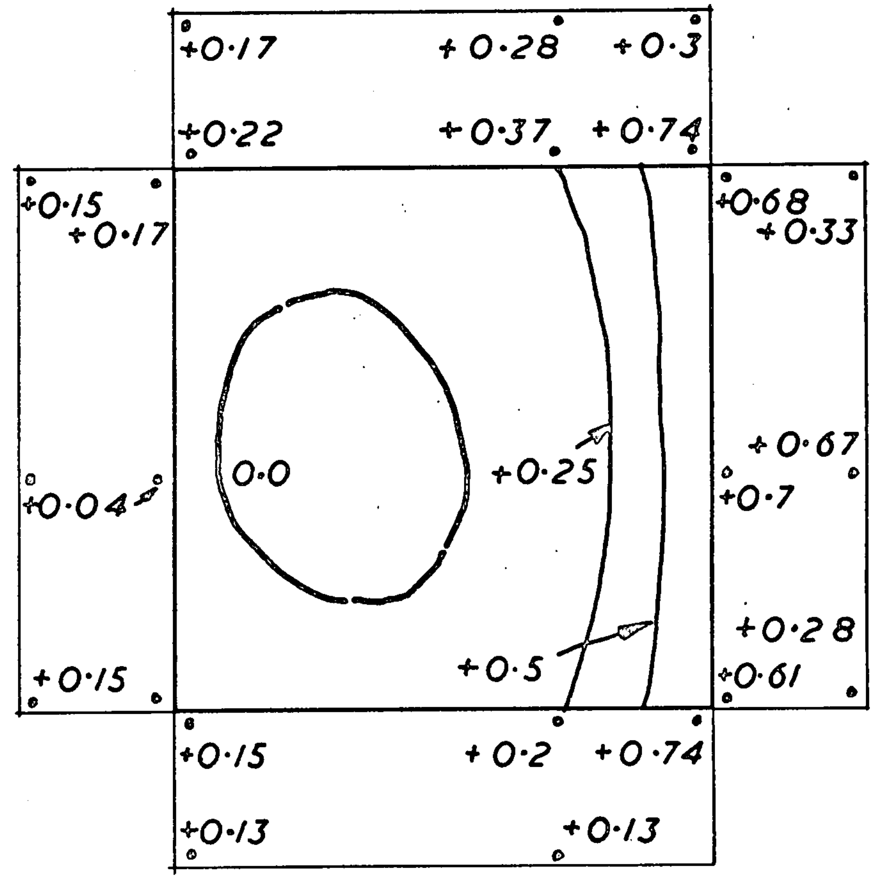


FIG 69B GEOM 18 → WIND

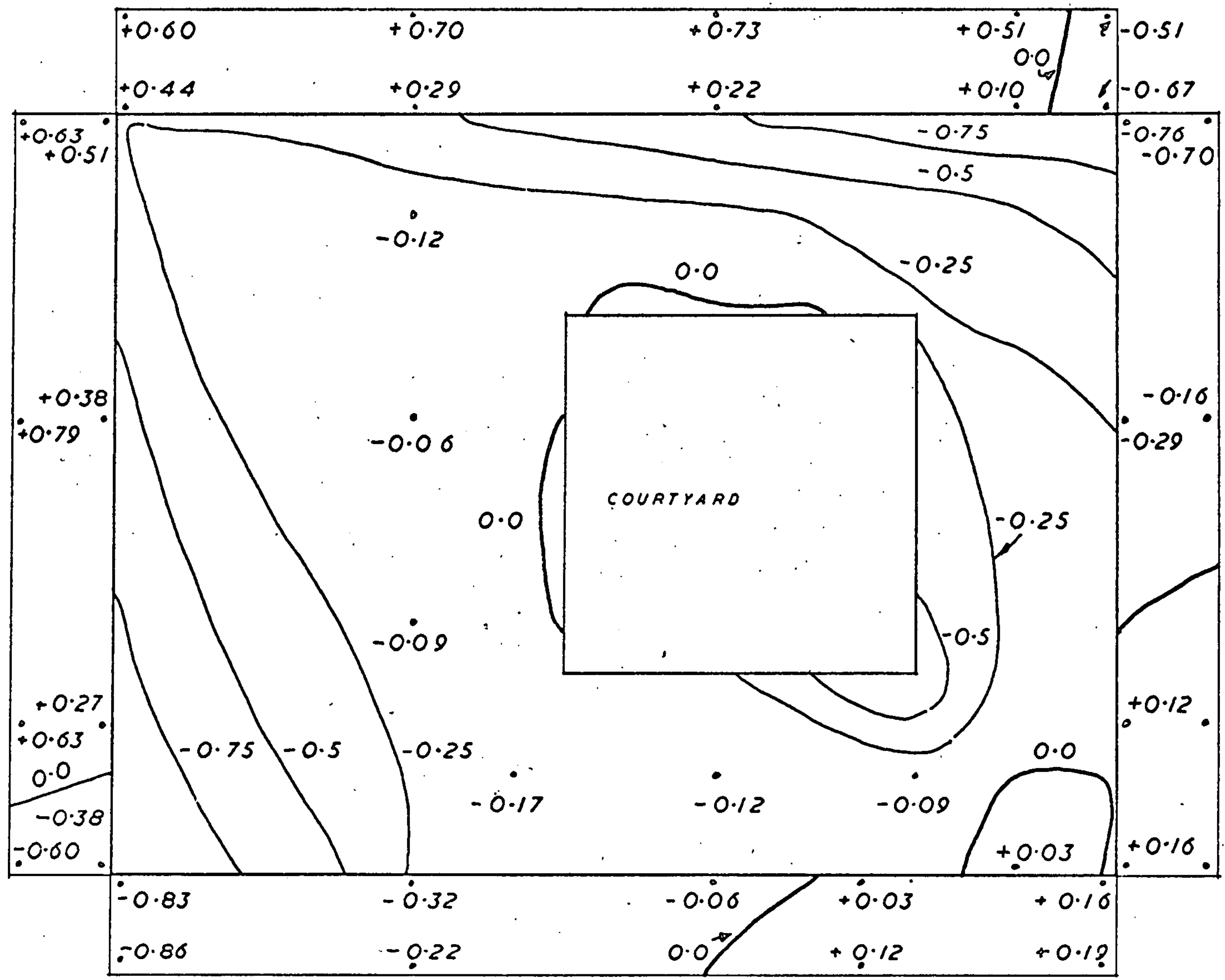


FIG 70A PRESSURE PATTERN GEOM 18 ↘ WIND

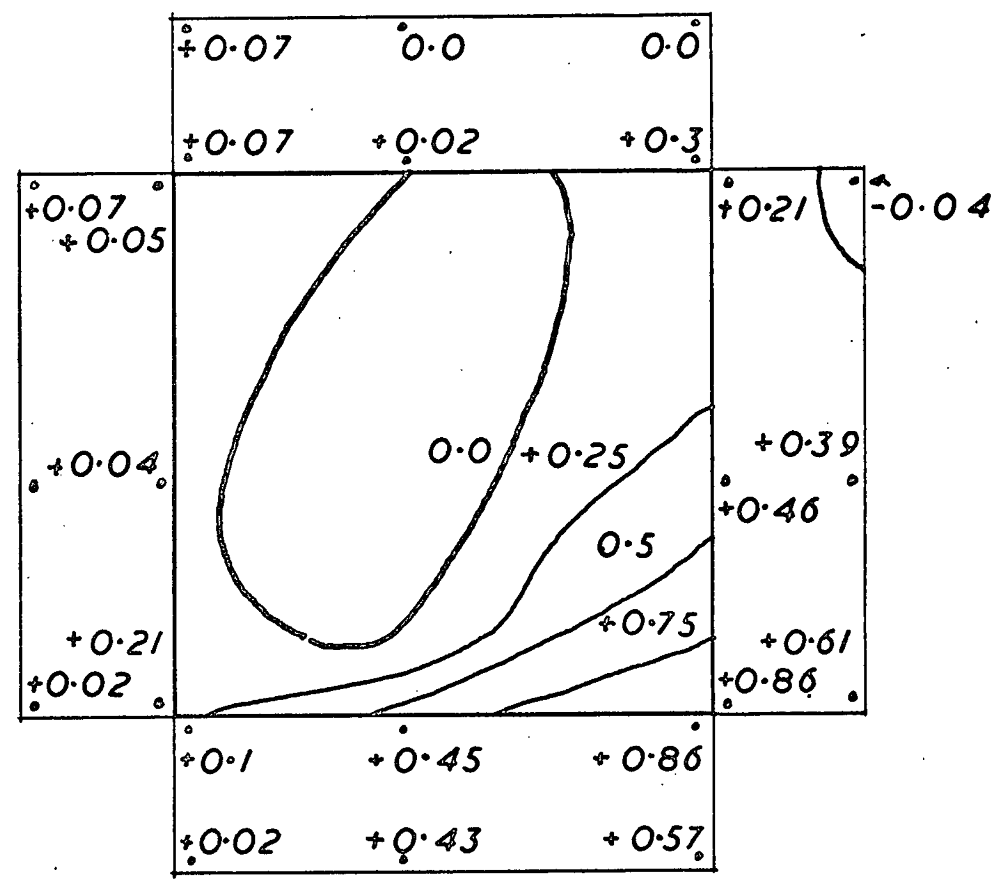


FIG 70B GEOM 18 ↘ WIND

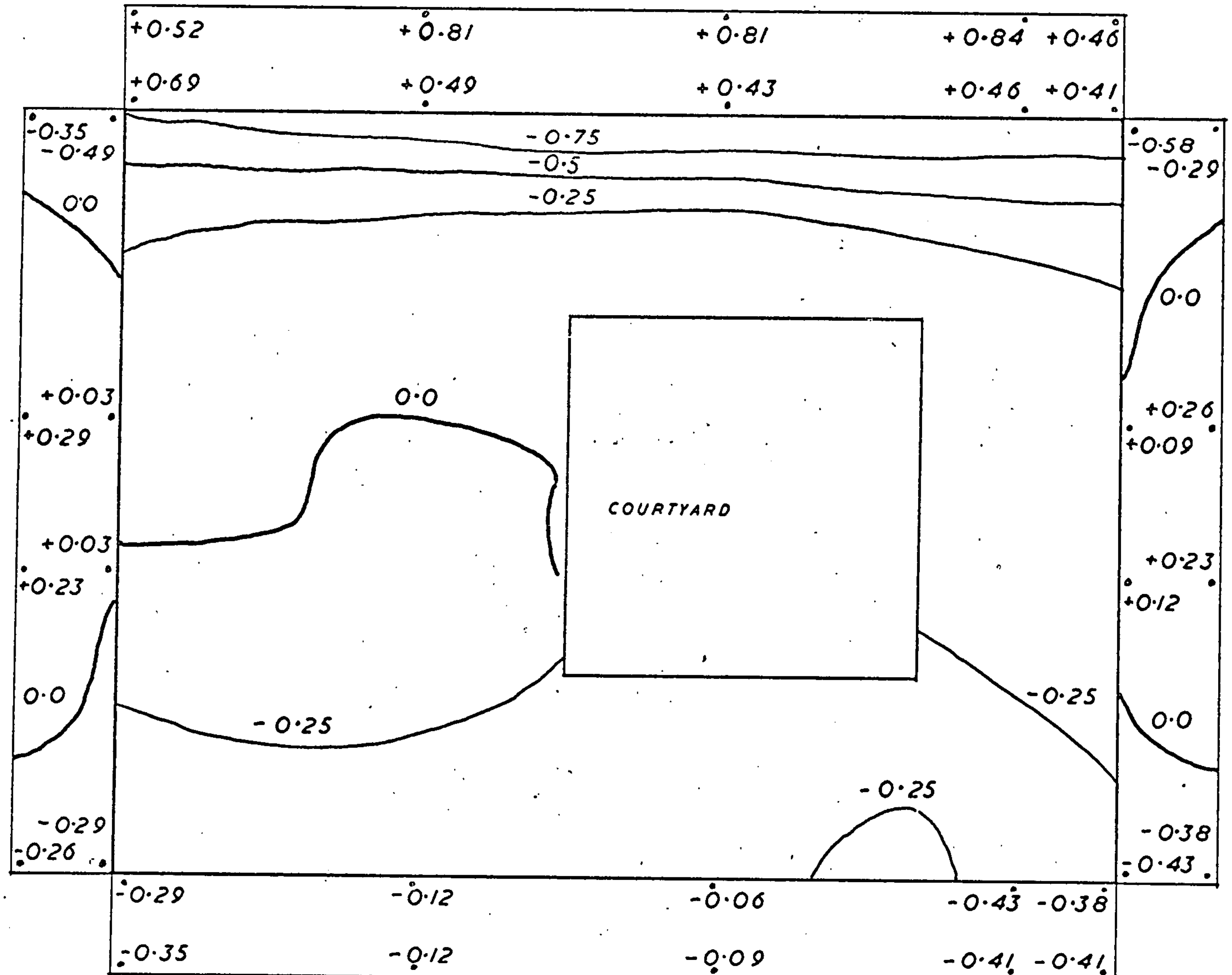


FIG 71A PRESSURE PATTERN GEOM 18 ↓ WIND

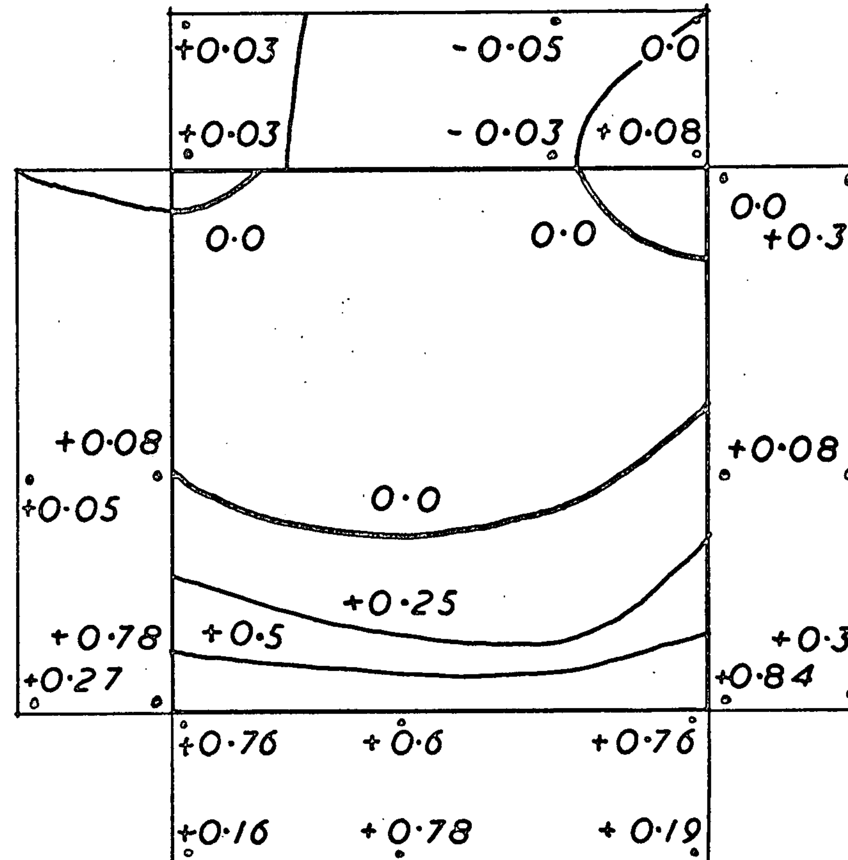


FIG 71B GEOM 18 ↓ WIND

N

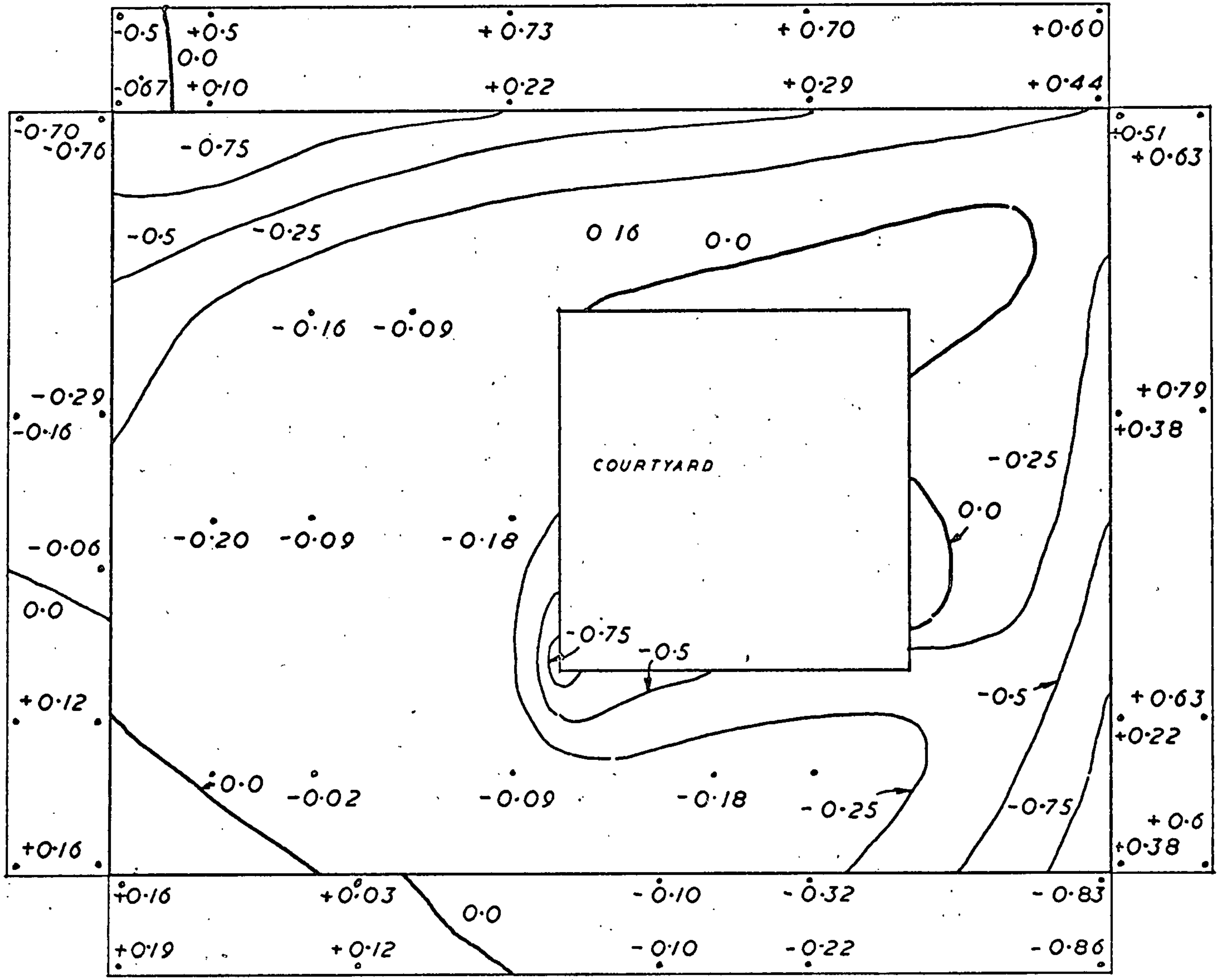


FIG 72 A PRESSURE PATTERN GEOM 18 ↙ WIND

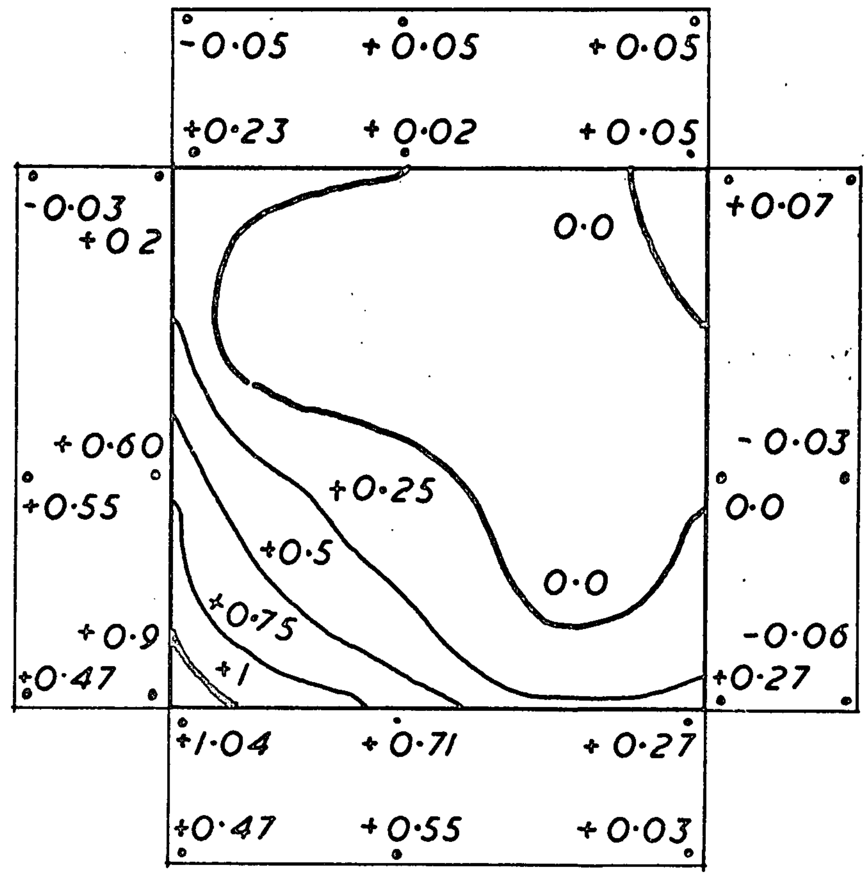


FIG 72 B GEOM 18 ∠ WIND

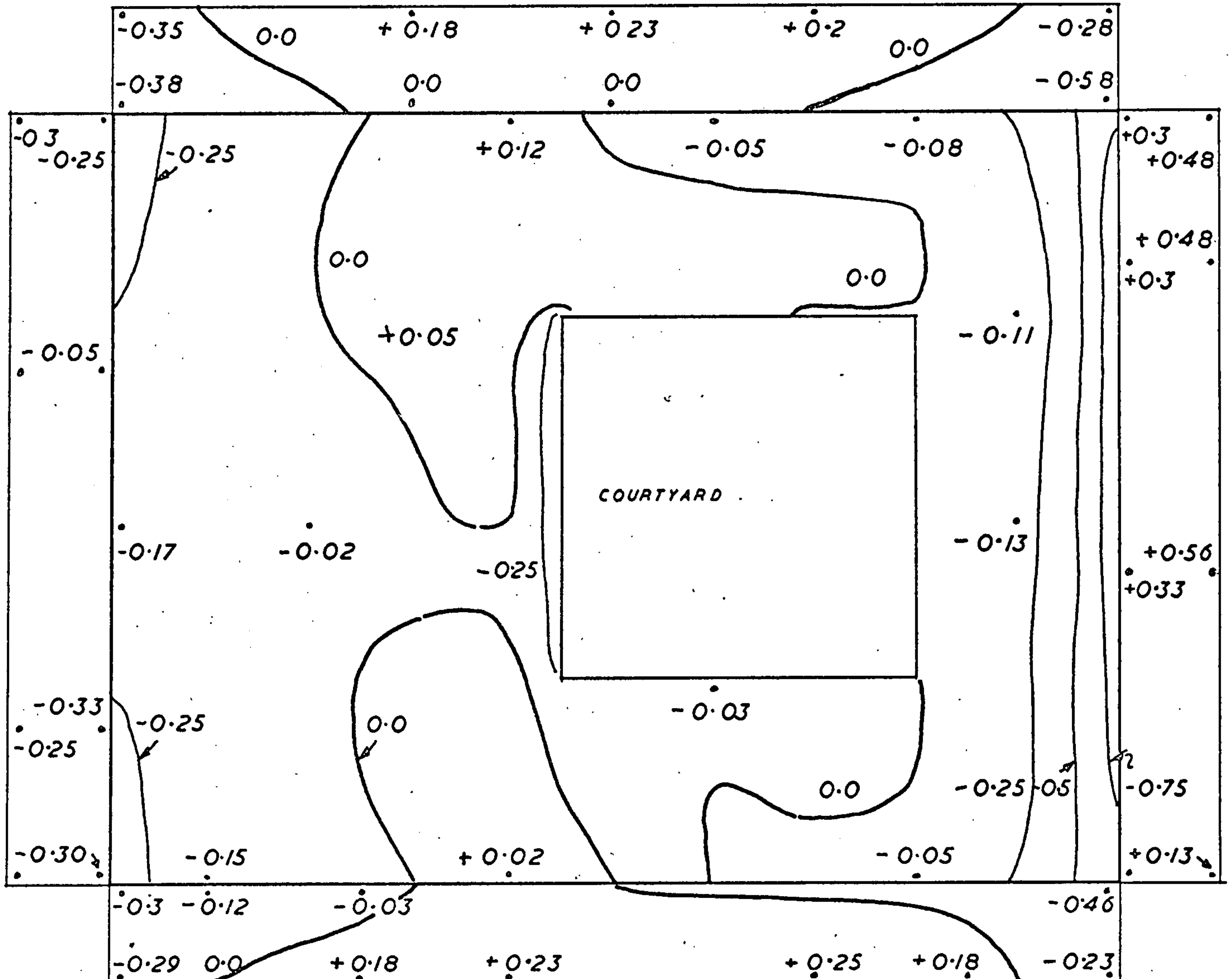


FIG 73A PRESSURE PATTERN GEOM 18 ← WIND

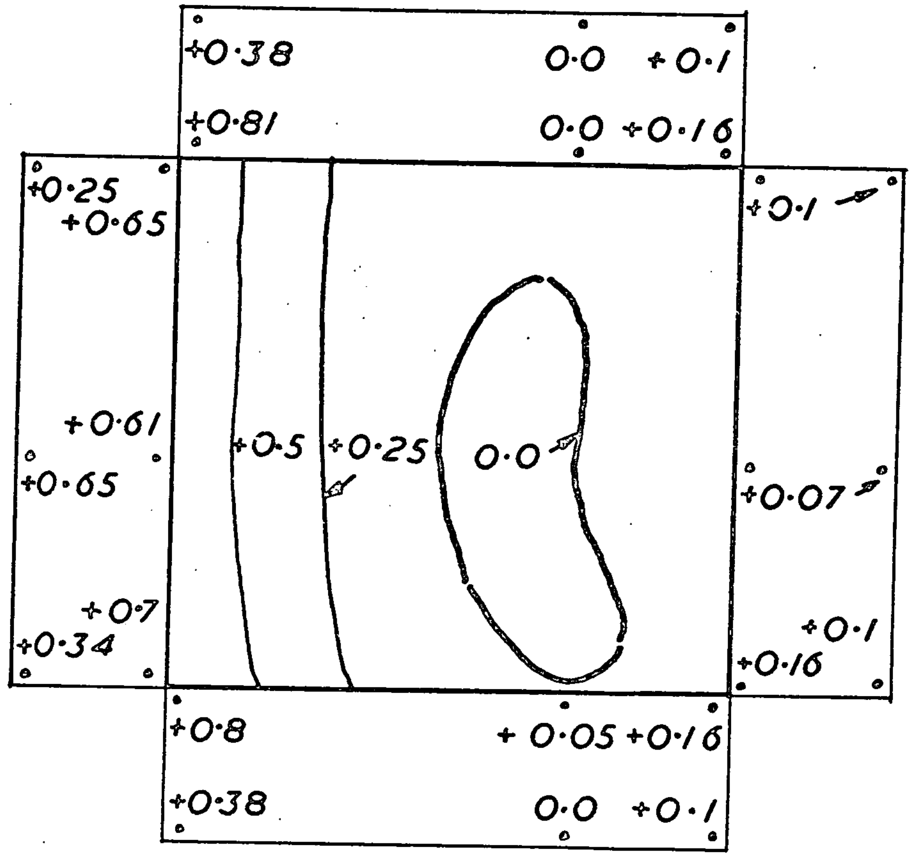


FIG 73B GEOM 18 ← WIND

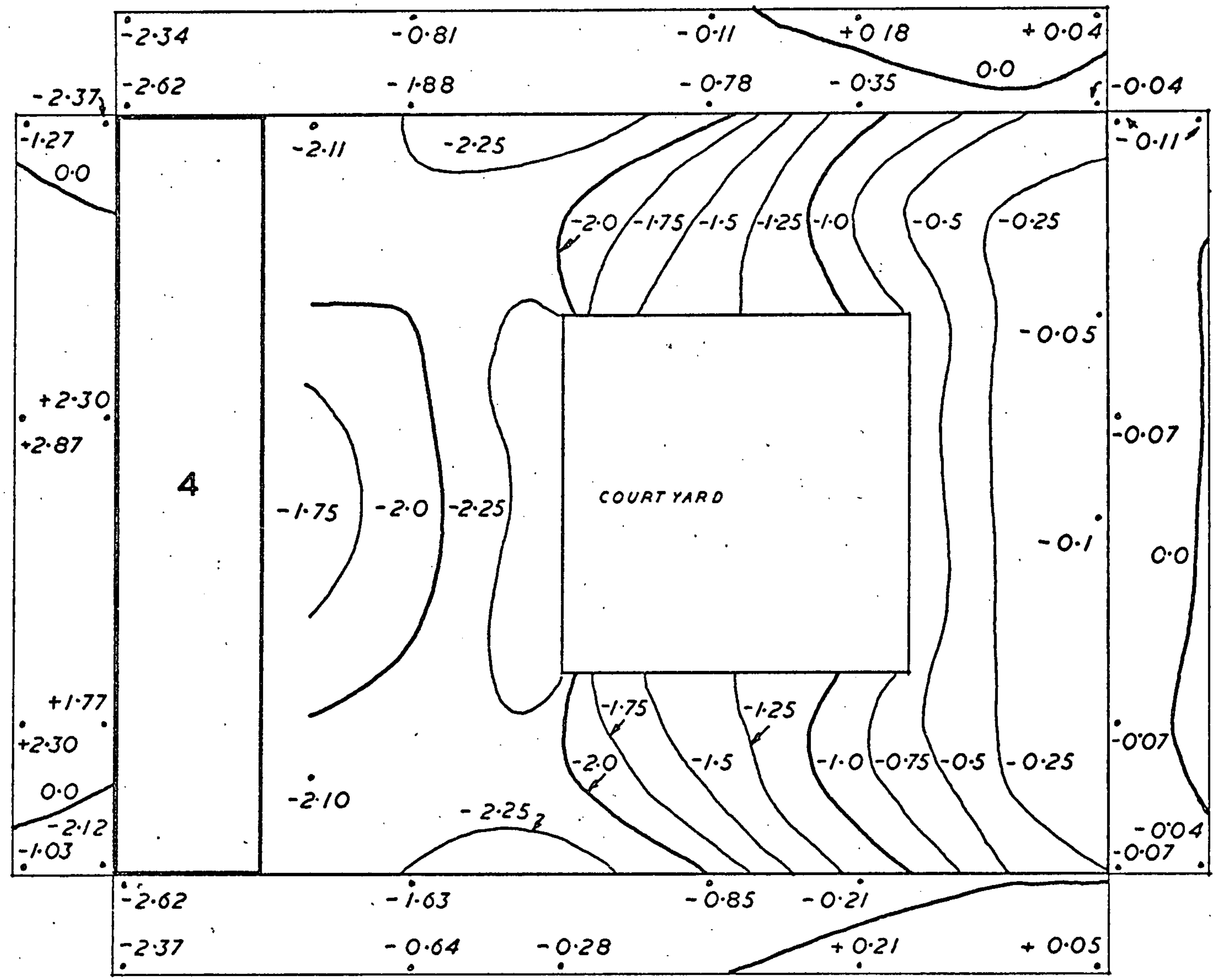


FIG 74A PRESSURE PATTERN GEOM 19 → WIND

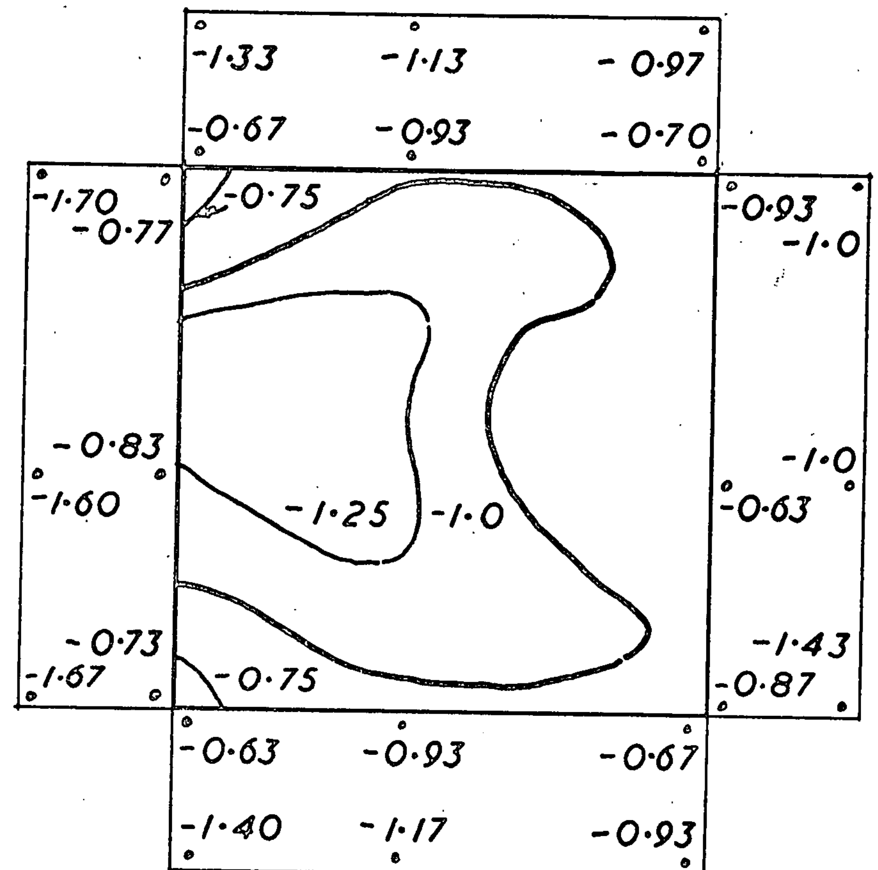


FIG 74B GEOM 19 → WIND

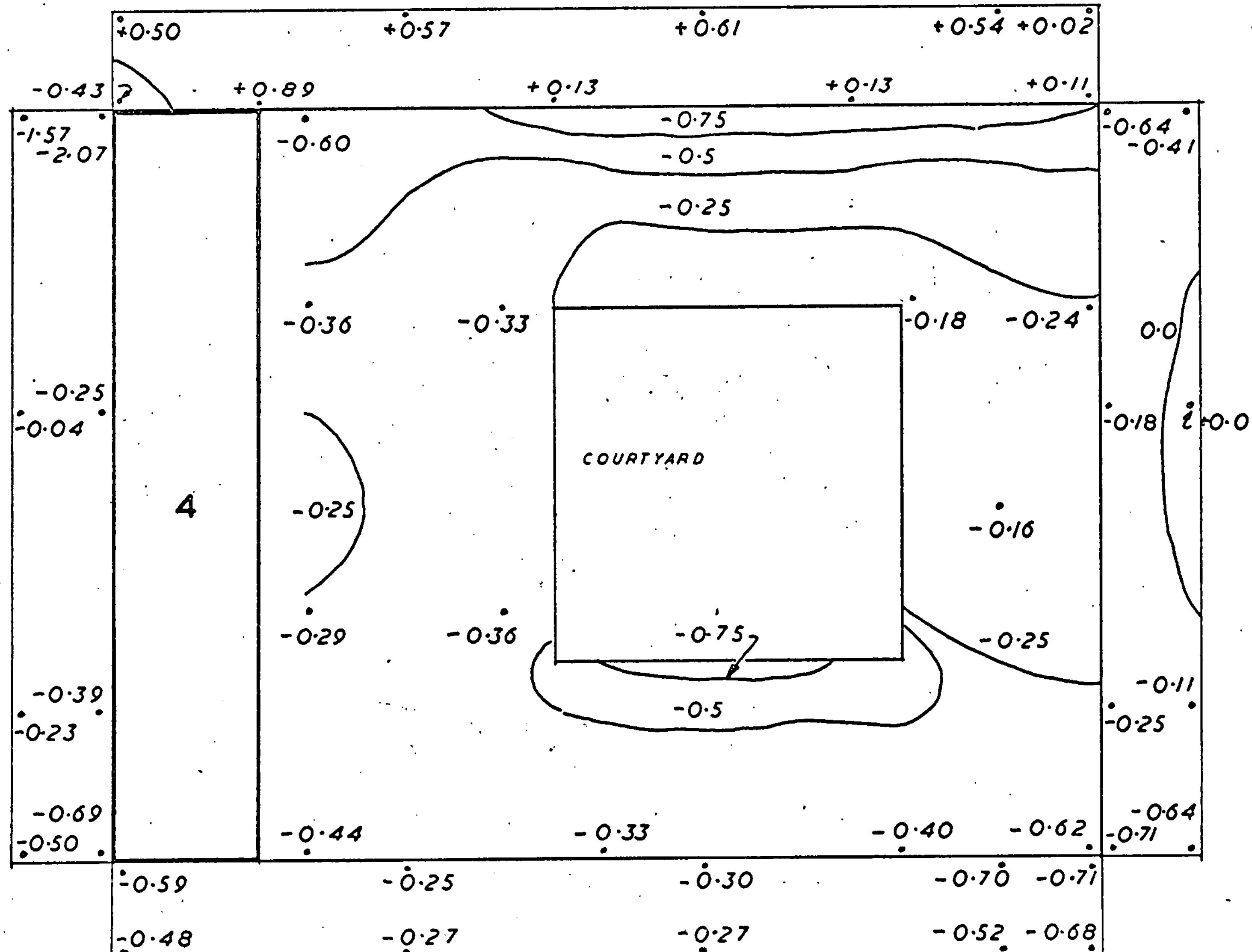


FIG 75A PRESSURE PATTERN GEOM 19 ↓ WIND

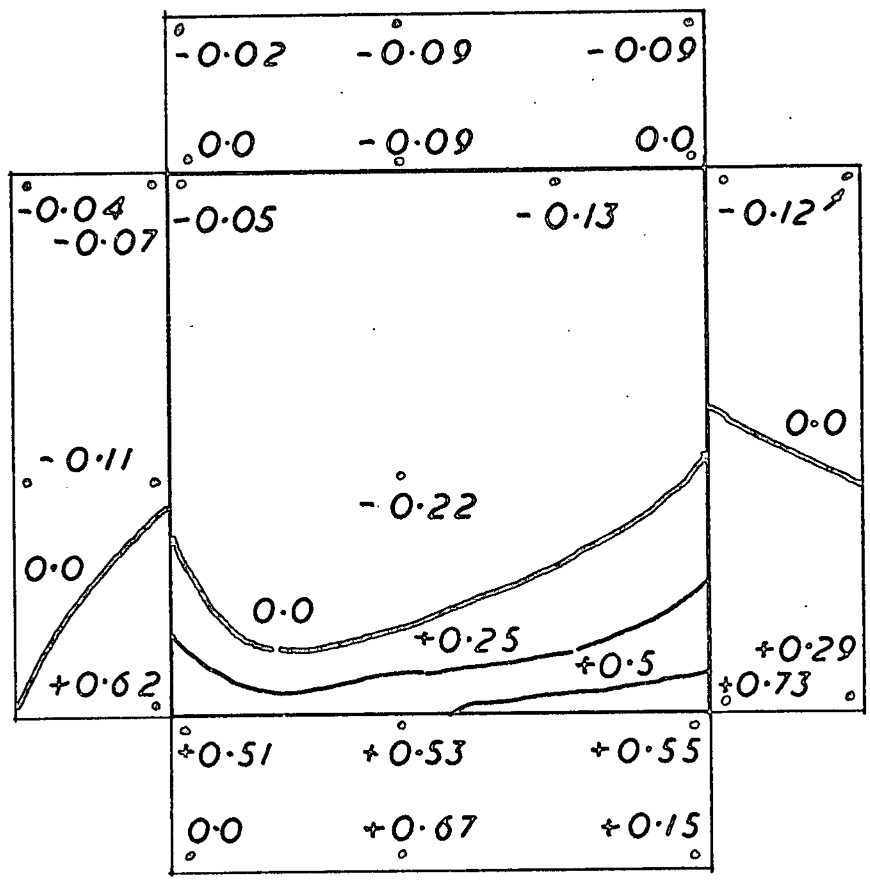


FIG 75B GEOM 19 ↓ WIND

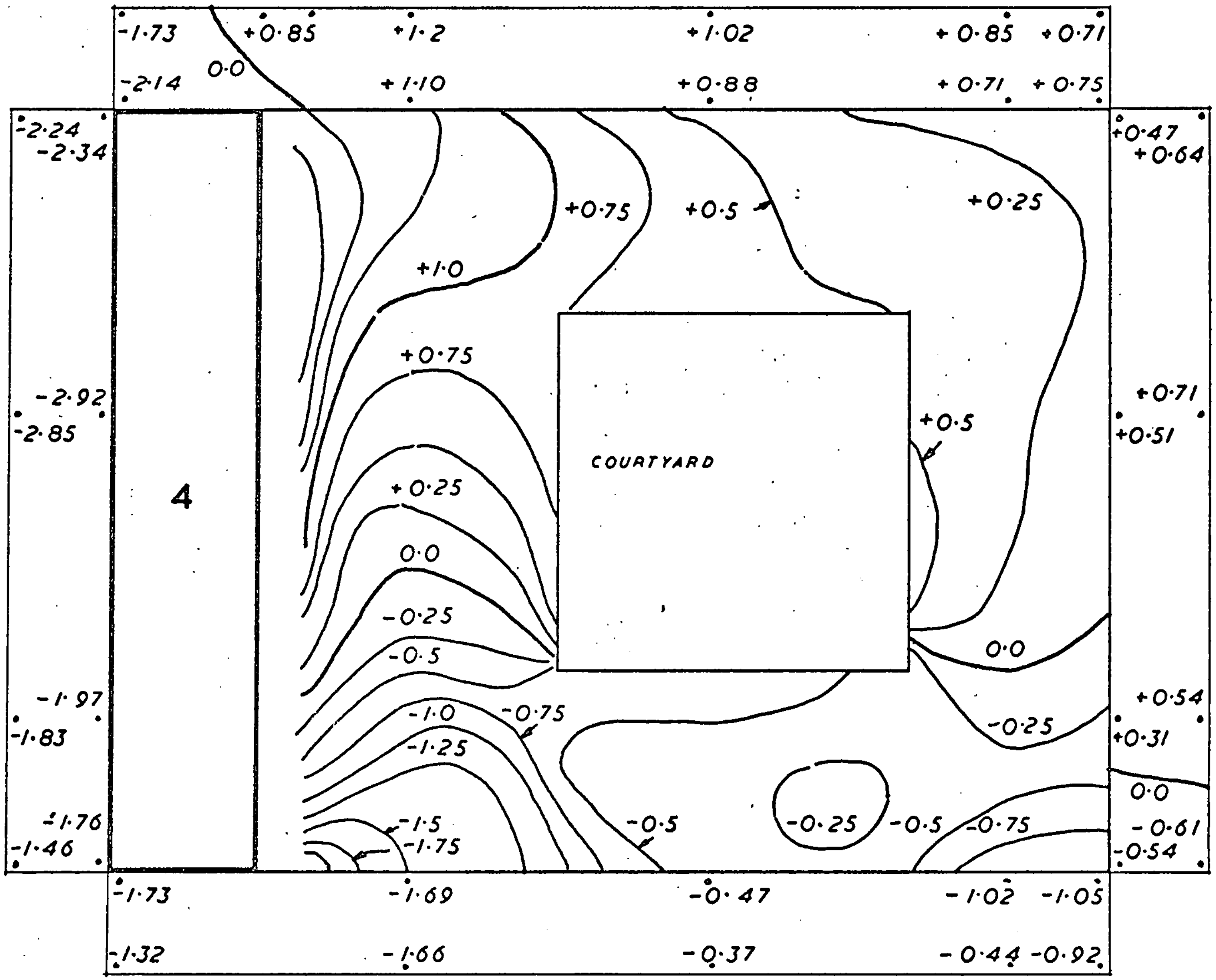


FIG 76A PRESSURE PATTERN GEOM 19 ↙ WIND

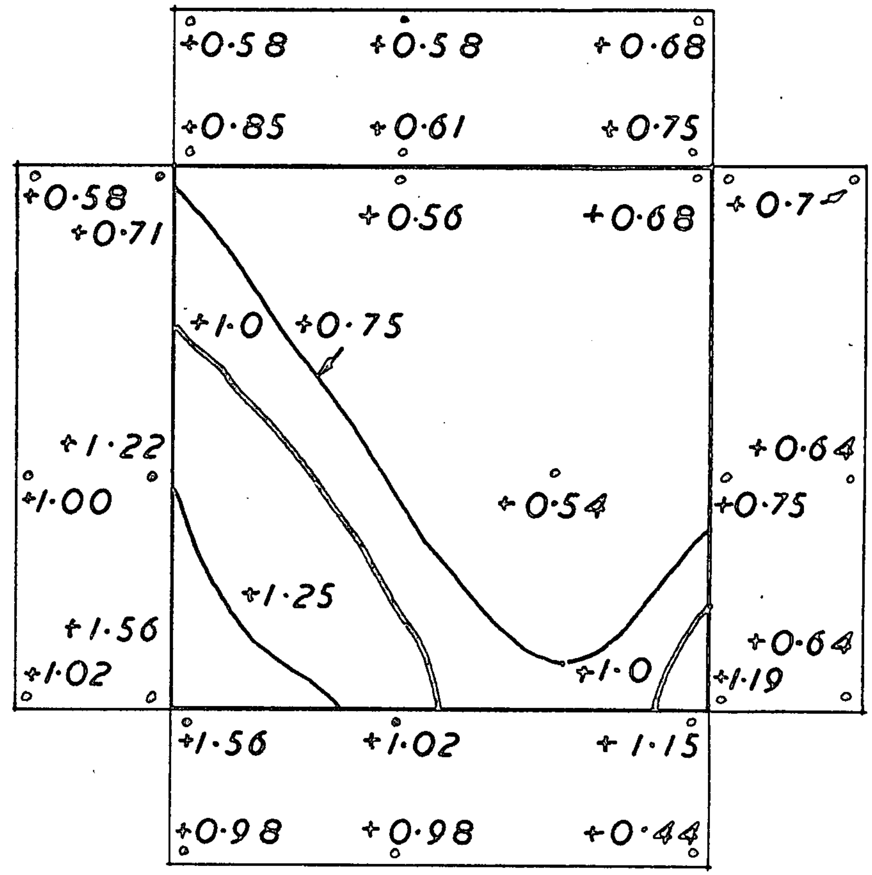


FIG 76B GEOM 19 WIND

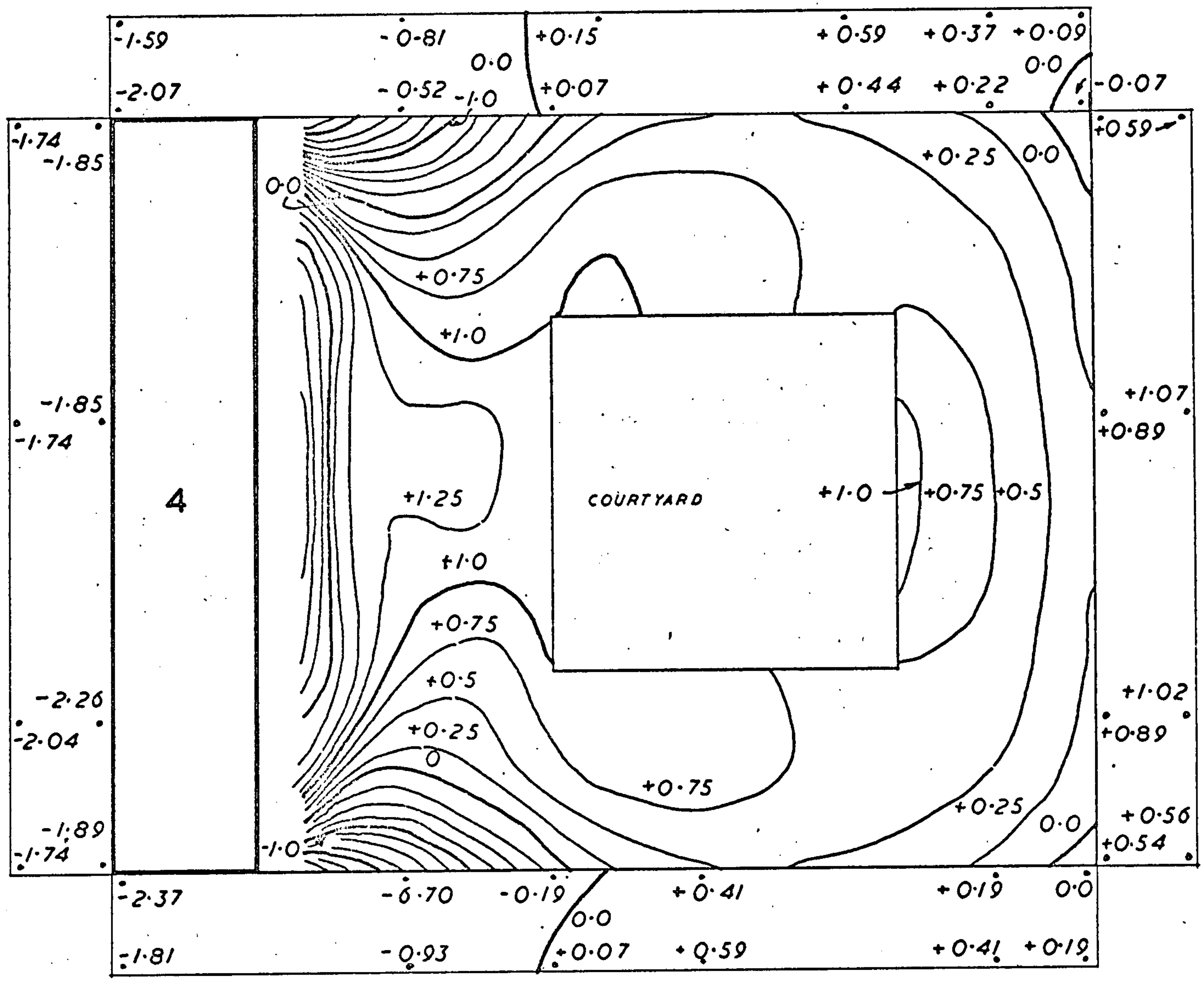


FIG 77A PRESSURE PATTERN GEOM 19 ← WIND

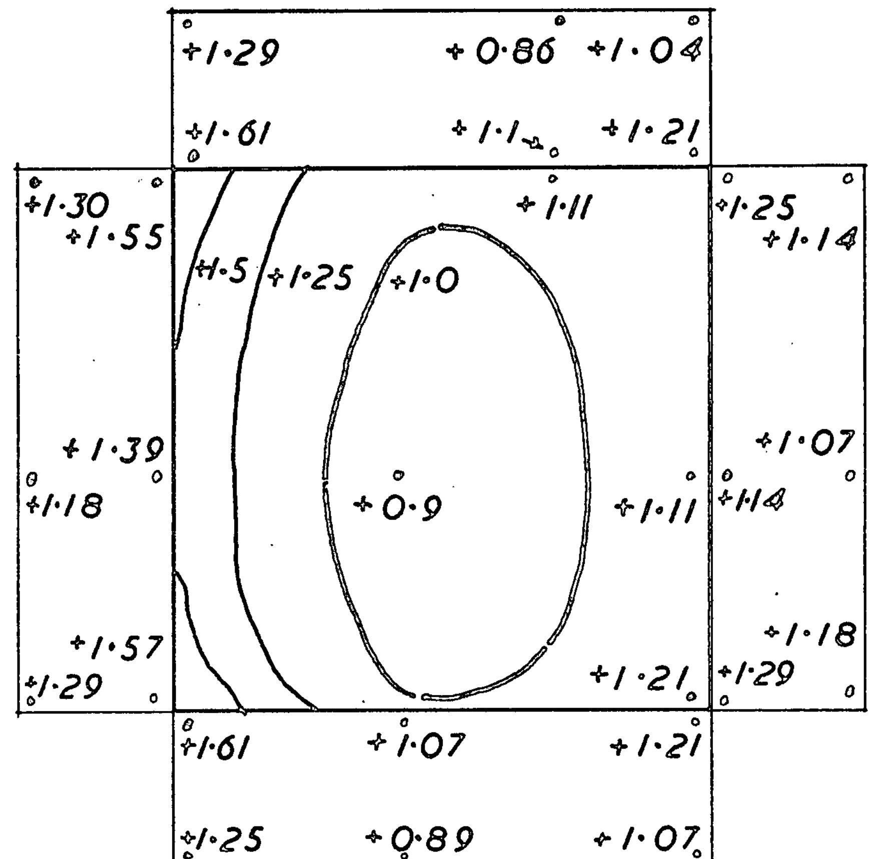


FIG 77B GEOM 19 ← WIND

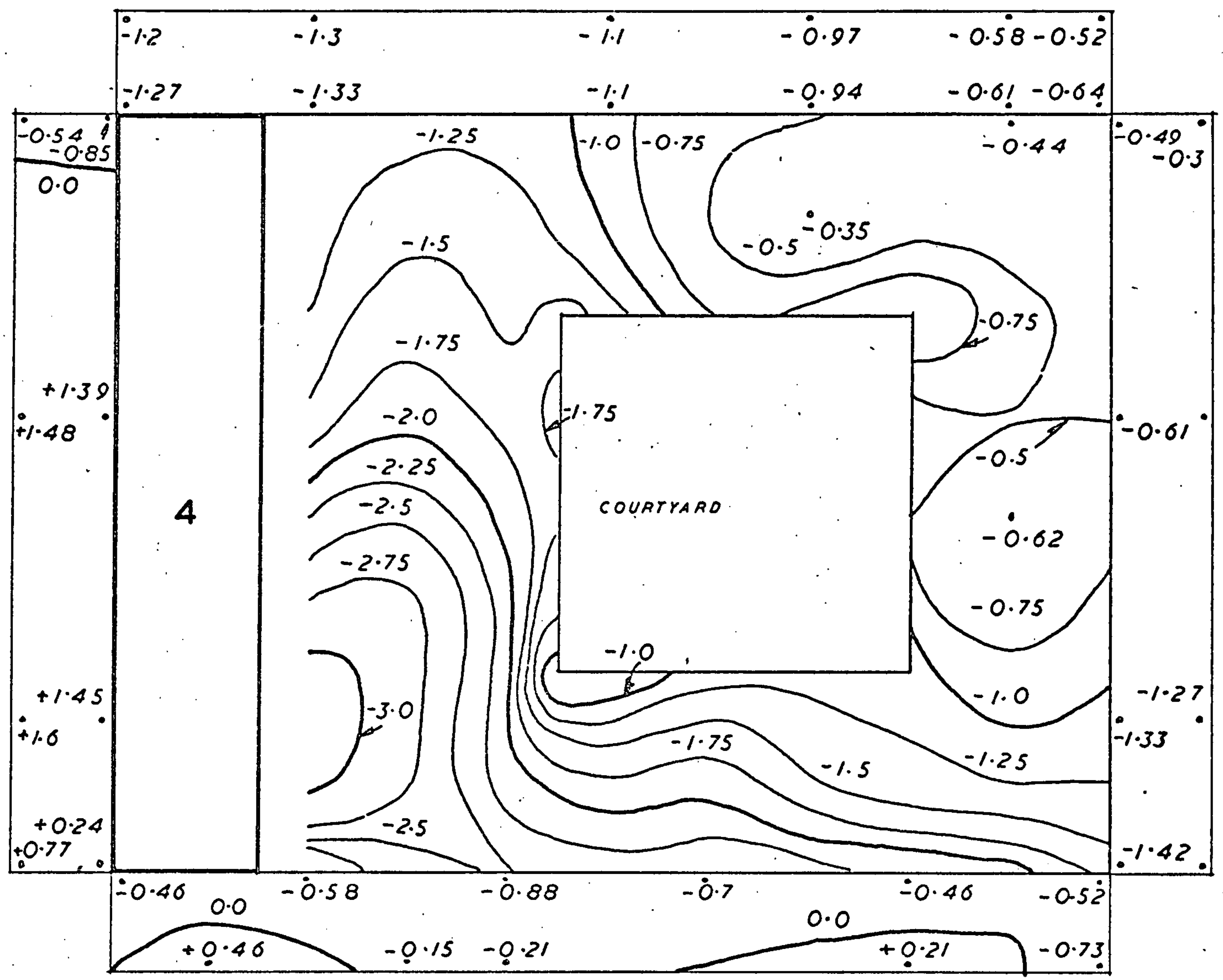


FIG 78A PRESSURE PATTERN GEOM 19 ↗ WIND

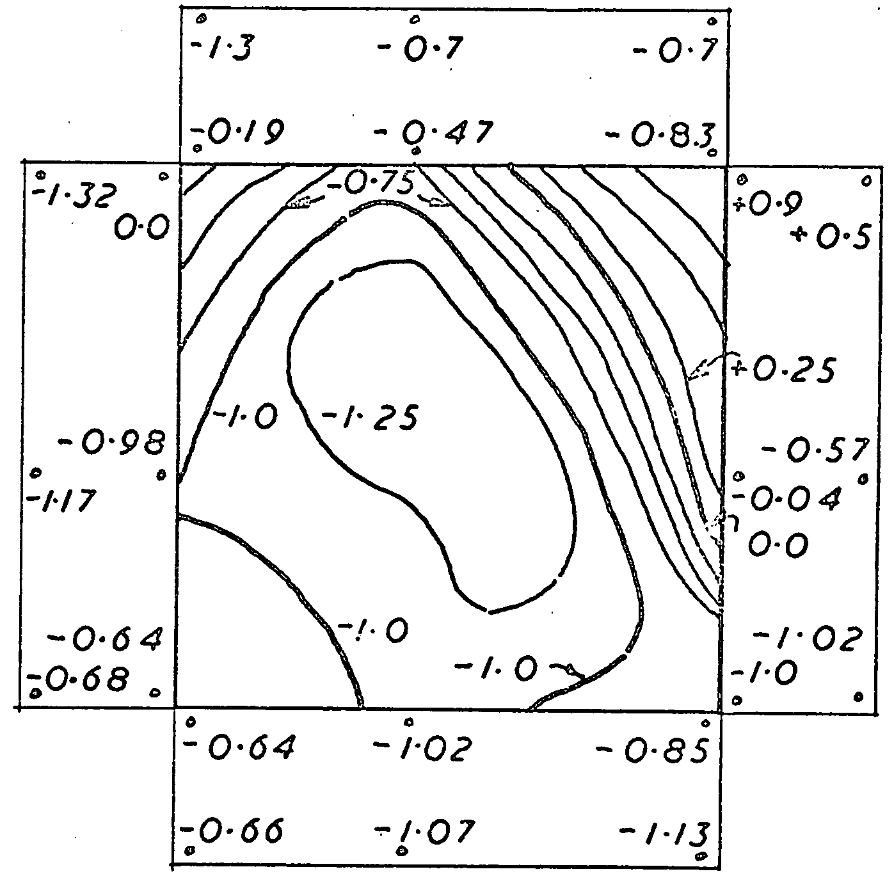
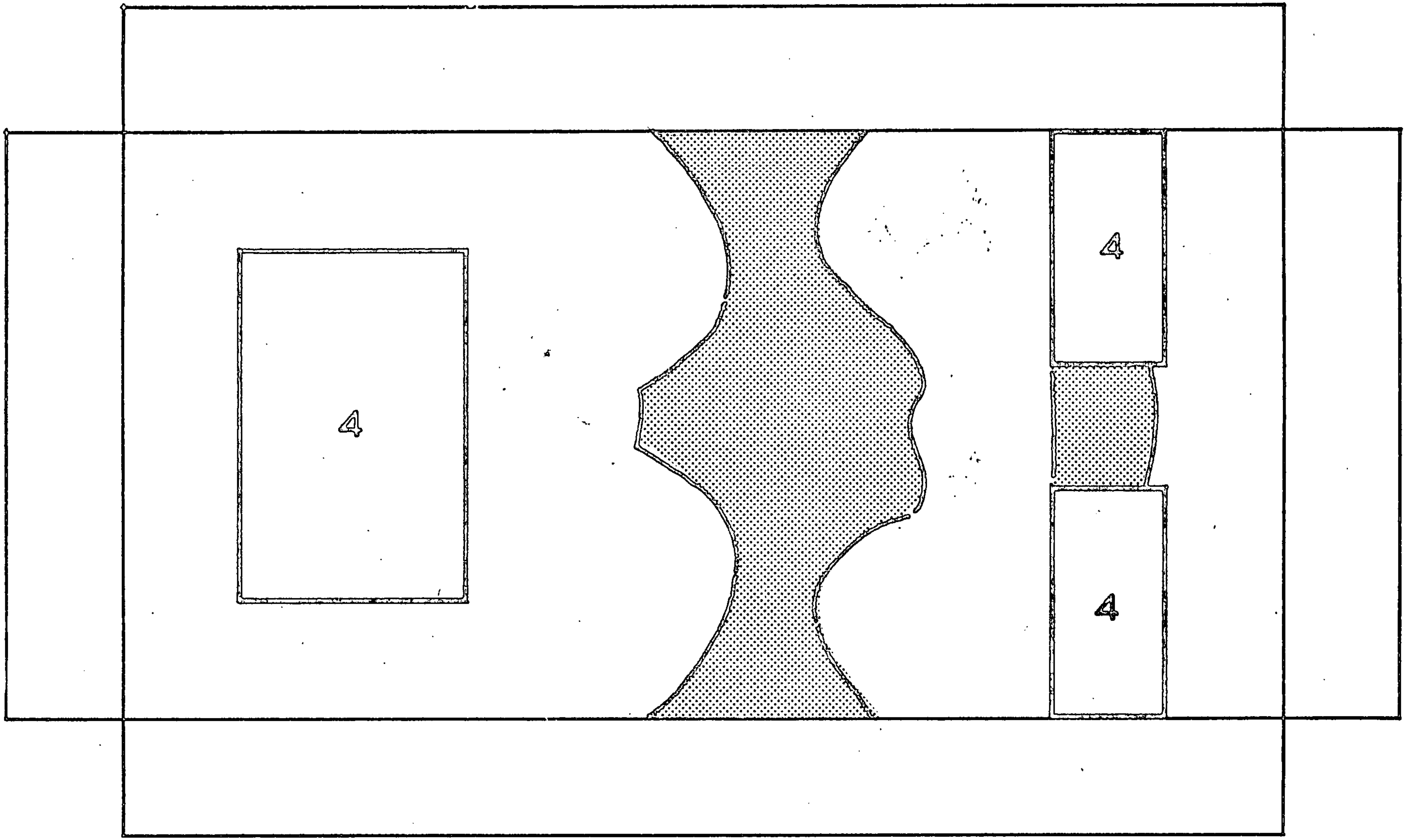


FIG 78B GEOM 19 ↗ WIND



GEOM 10
FIG 79 AREA OF NEGATIVE PRESSURE
CONSIDERING ALL WIND DIRECTIONS

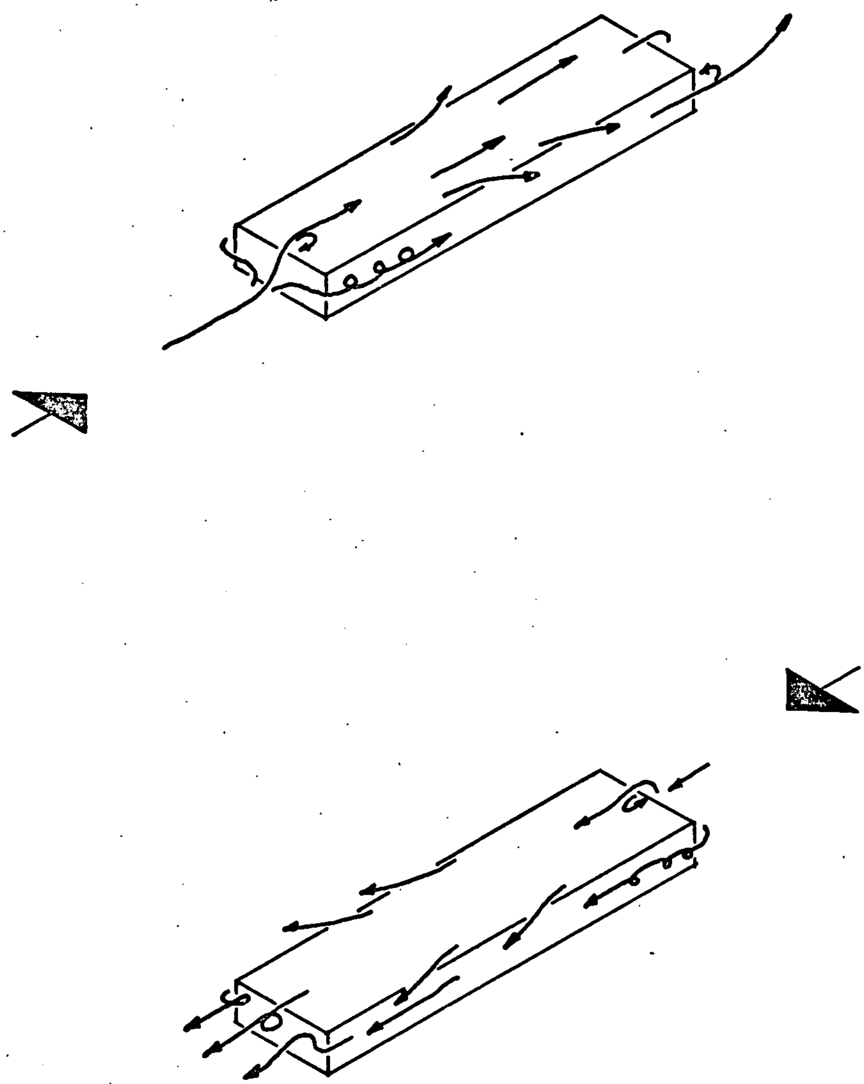


FIG 101 : GEOM 1 : WIND 0°

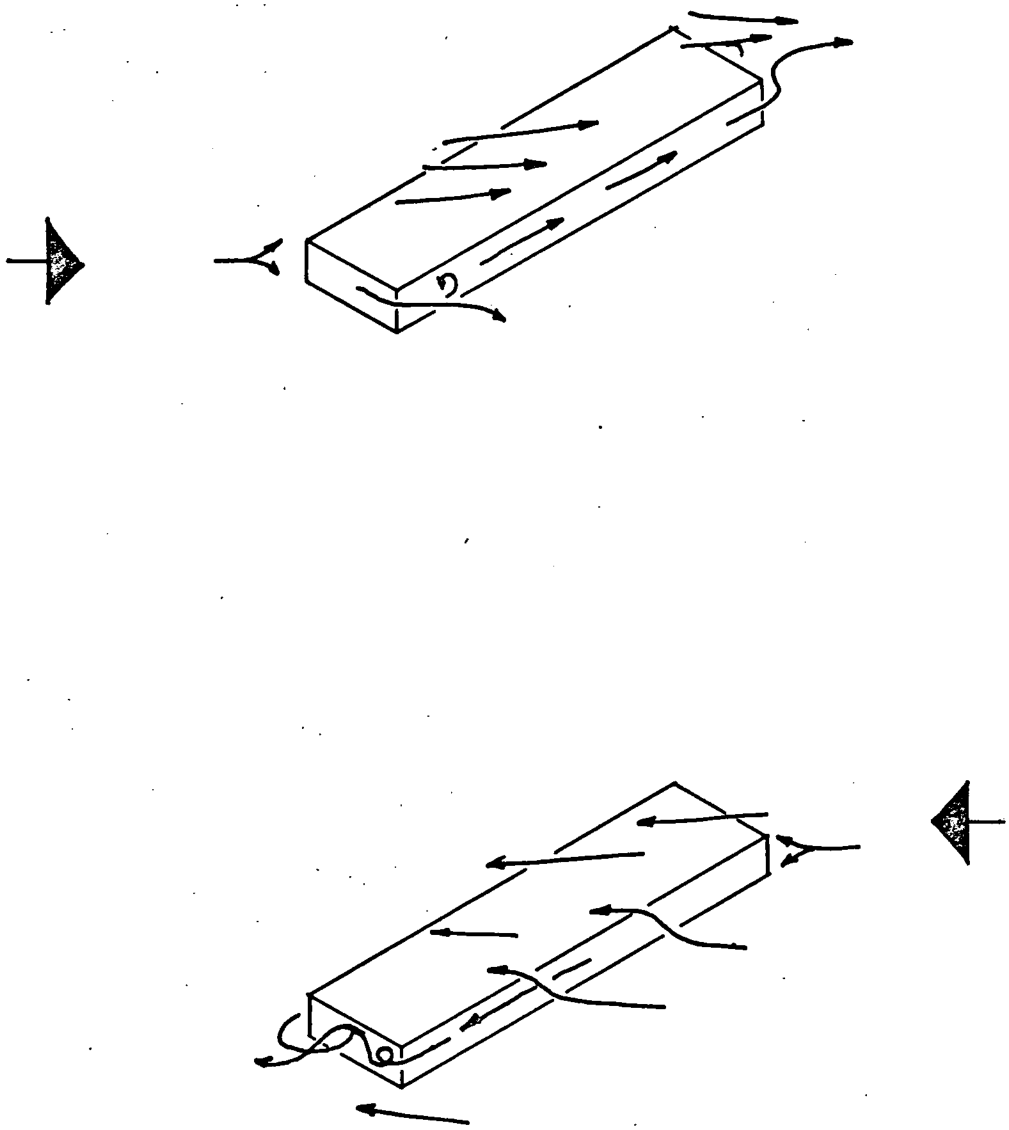


FIG 102 : GEOM 1 : WIND 315°

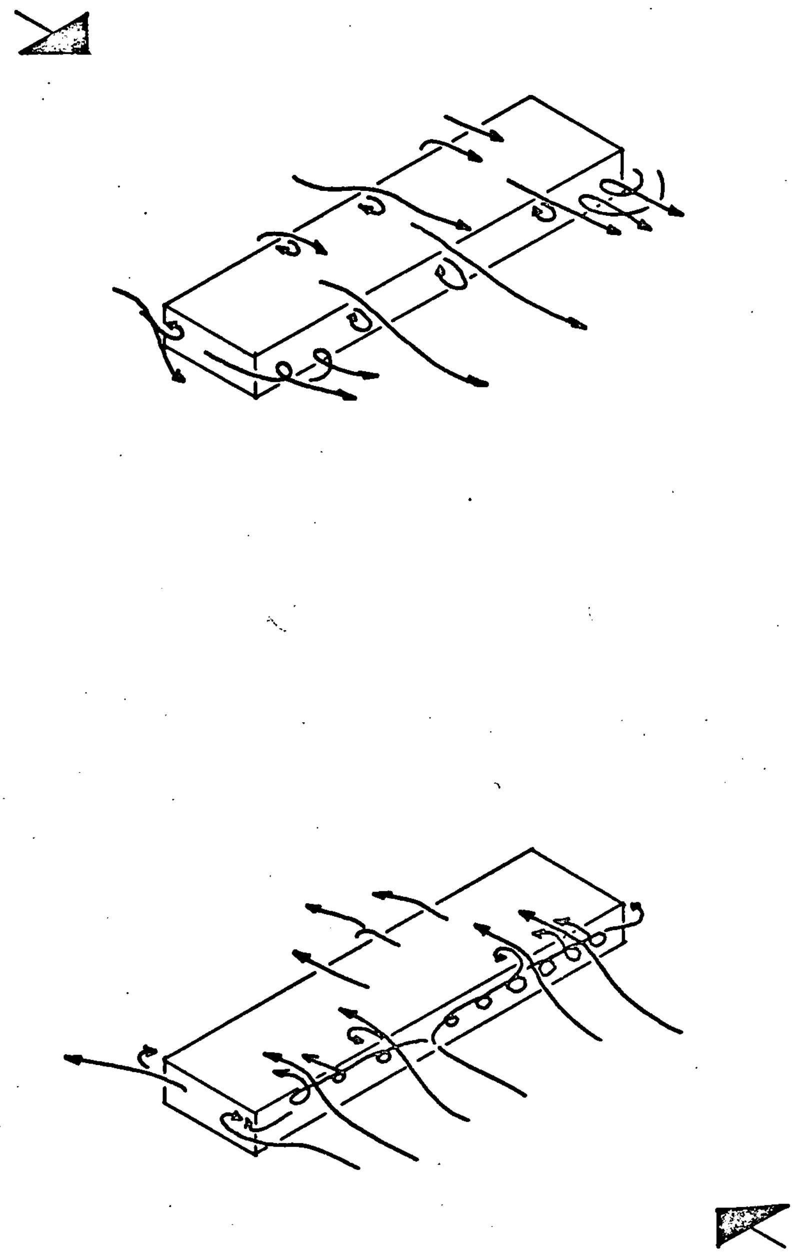


FIG 103 : GEOM 1 : WIND 270°

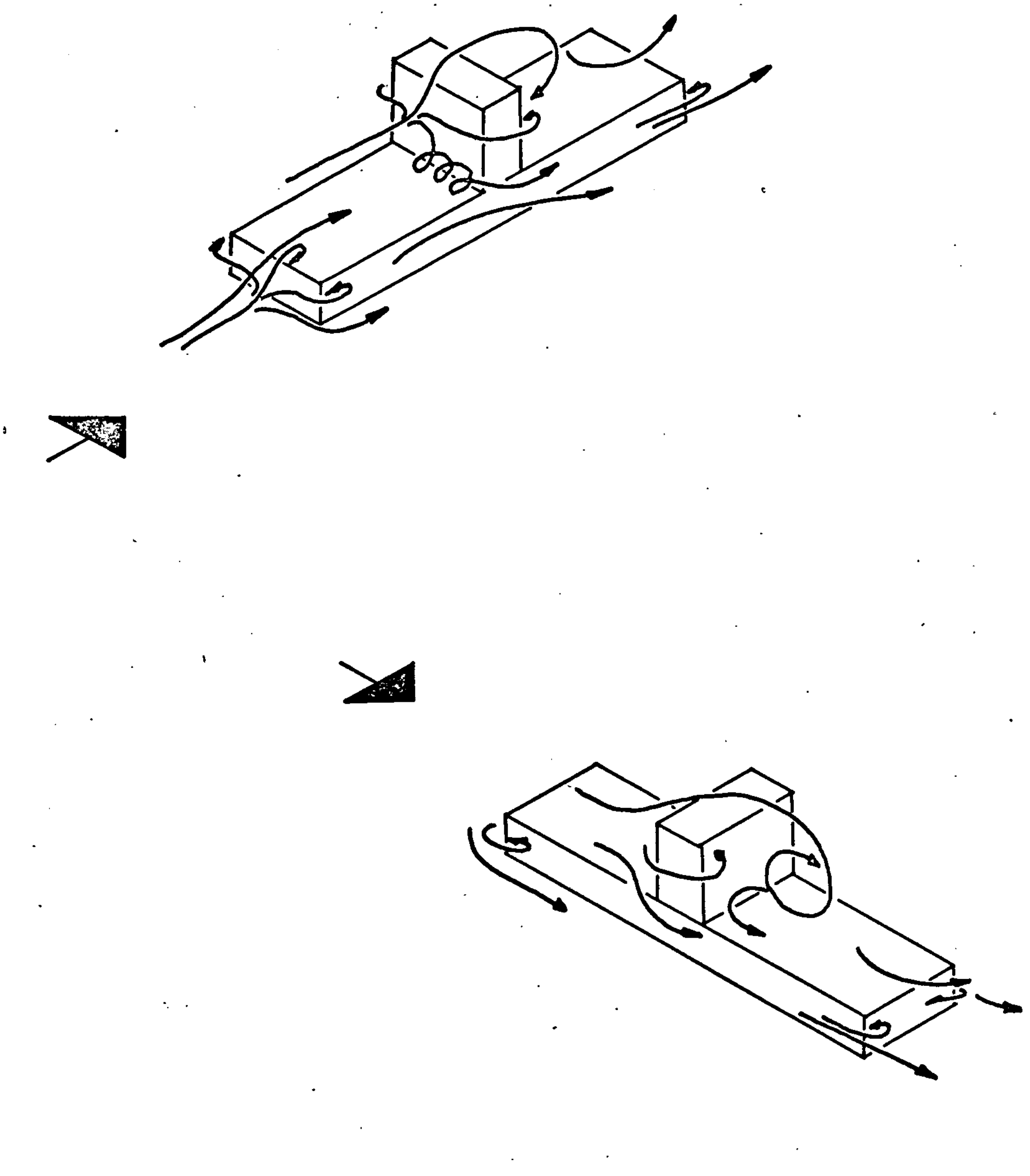
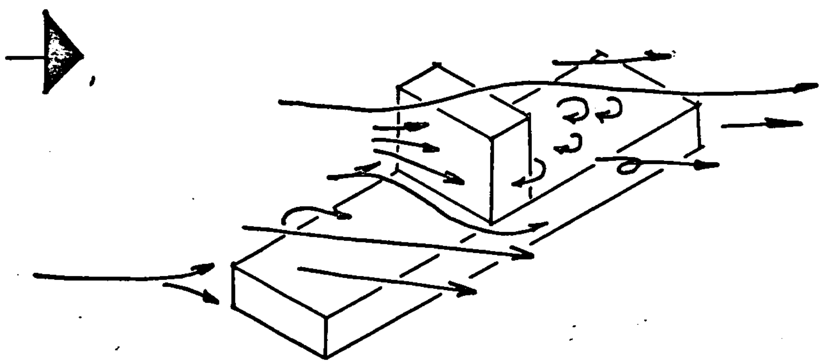


FIG 104 : GEOM 2 : WIND 0°



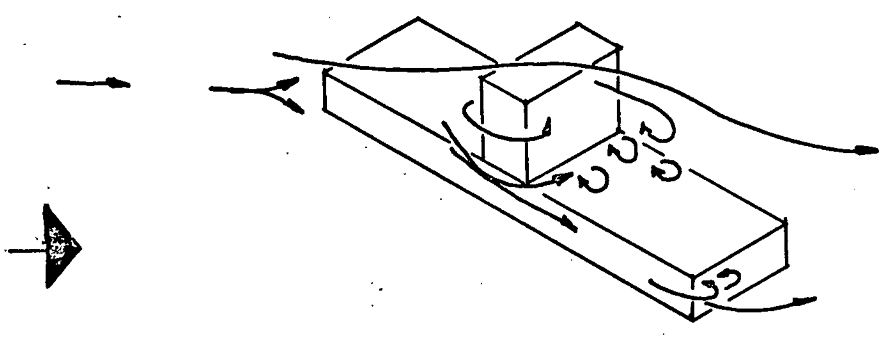
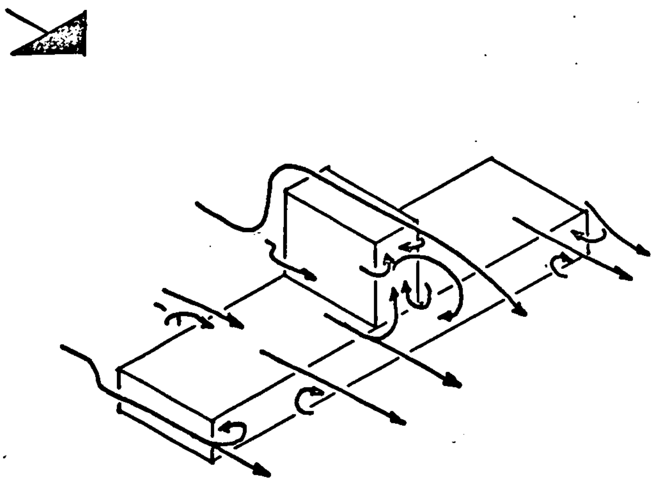


FIG 105 : GEOM 2 : WIND 315°



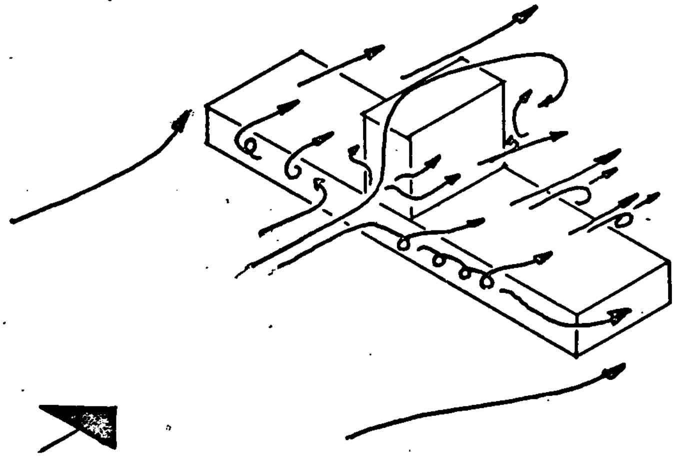


FIG 106 : GEOM 2 : WIND 270°

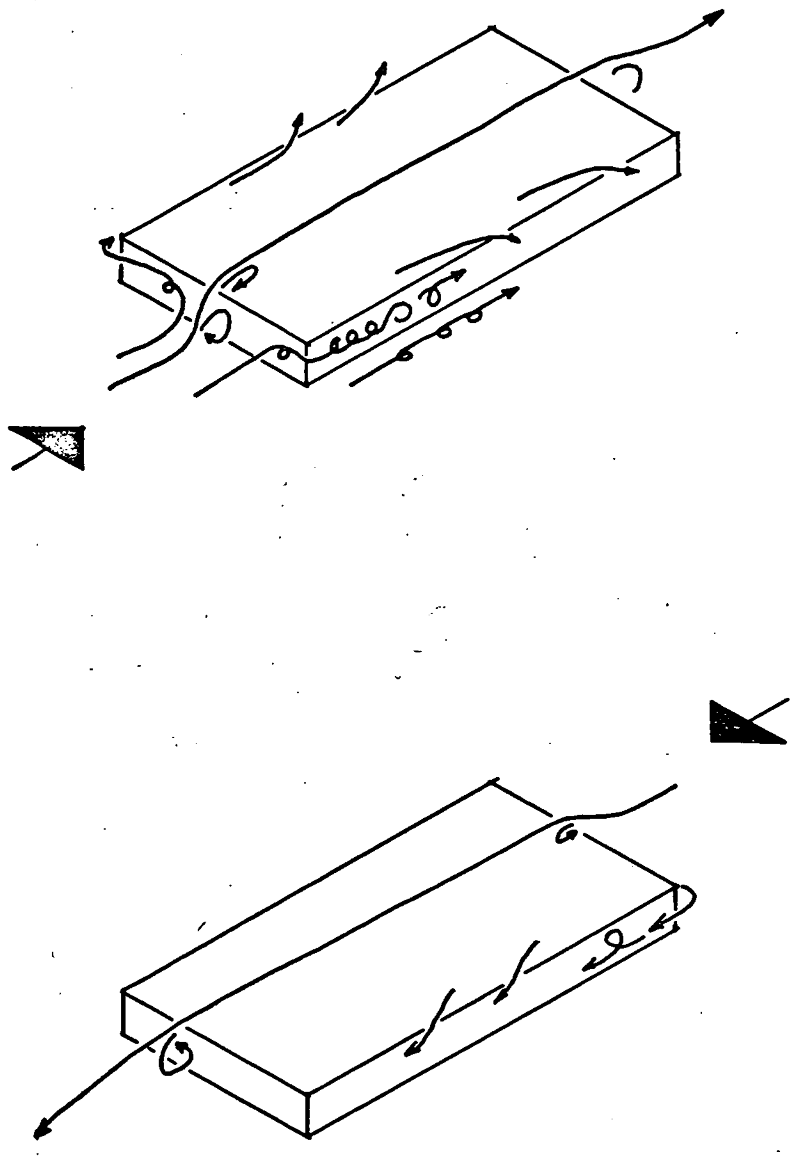


FIG 107 : GEOM 3 : WIND 0°

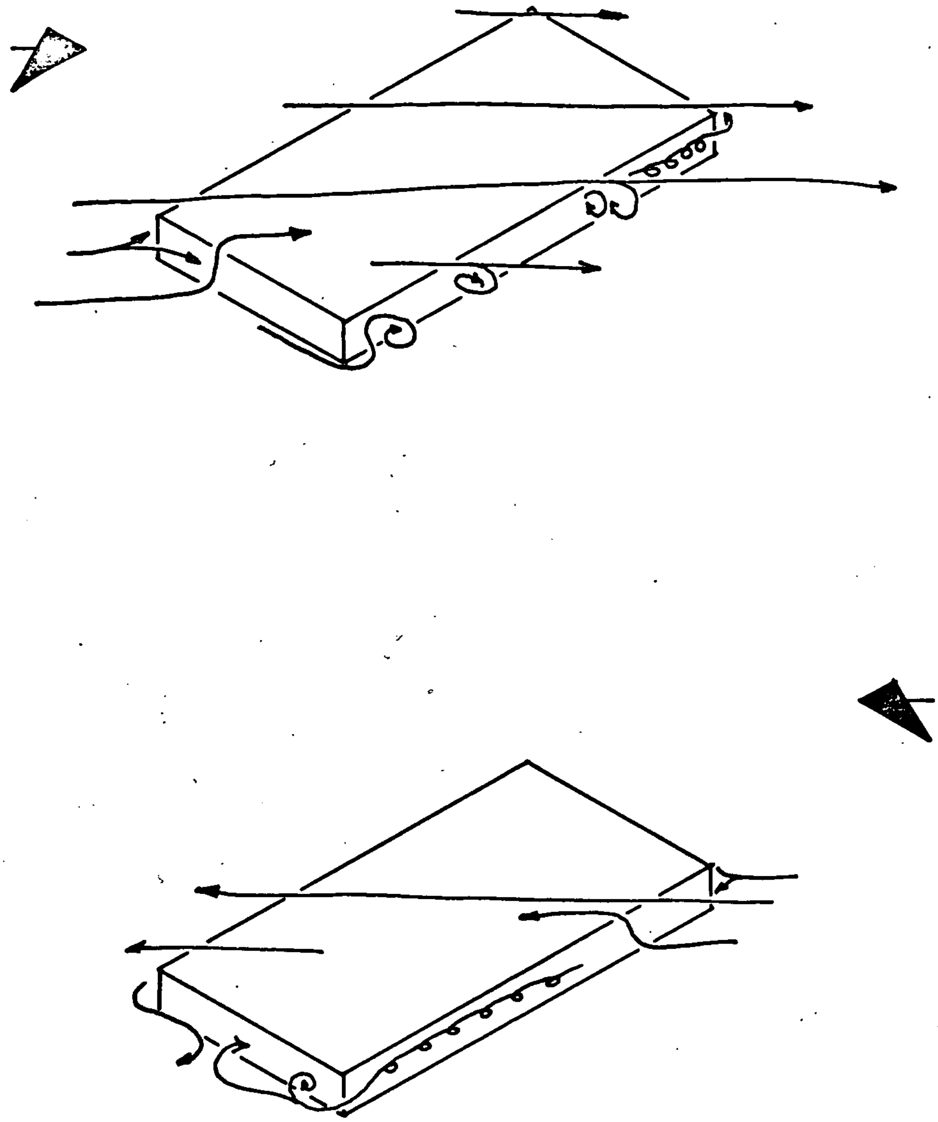


FIG 108 : GEOM 3 : WIND 45°

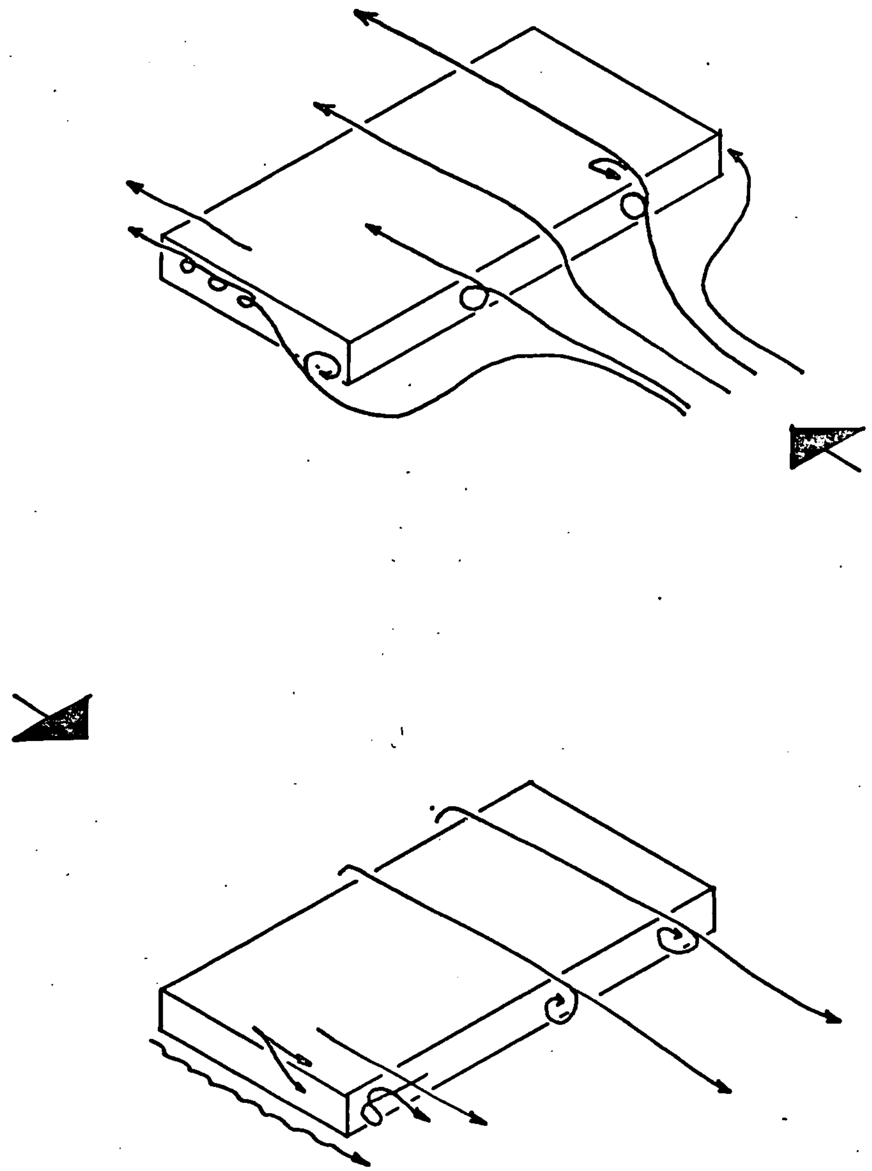


FIG 109 : GEOM 3 : WIND 90°

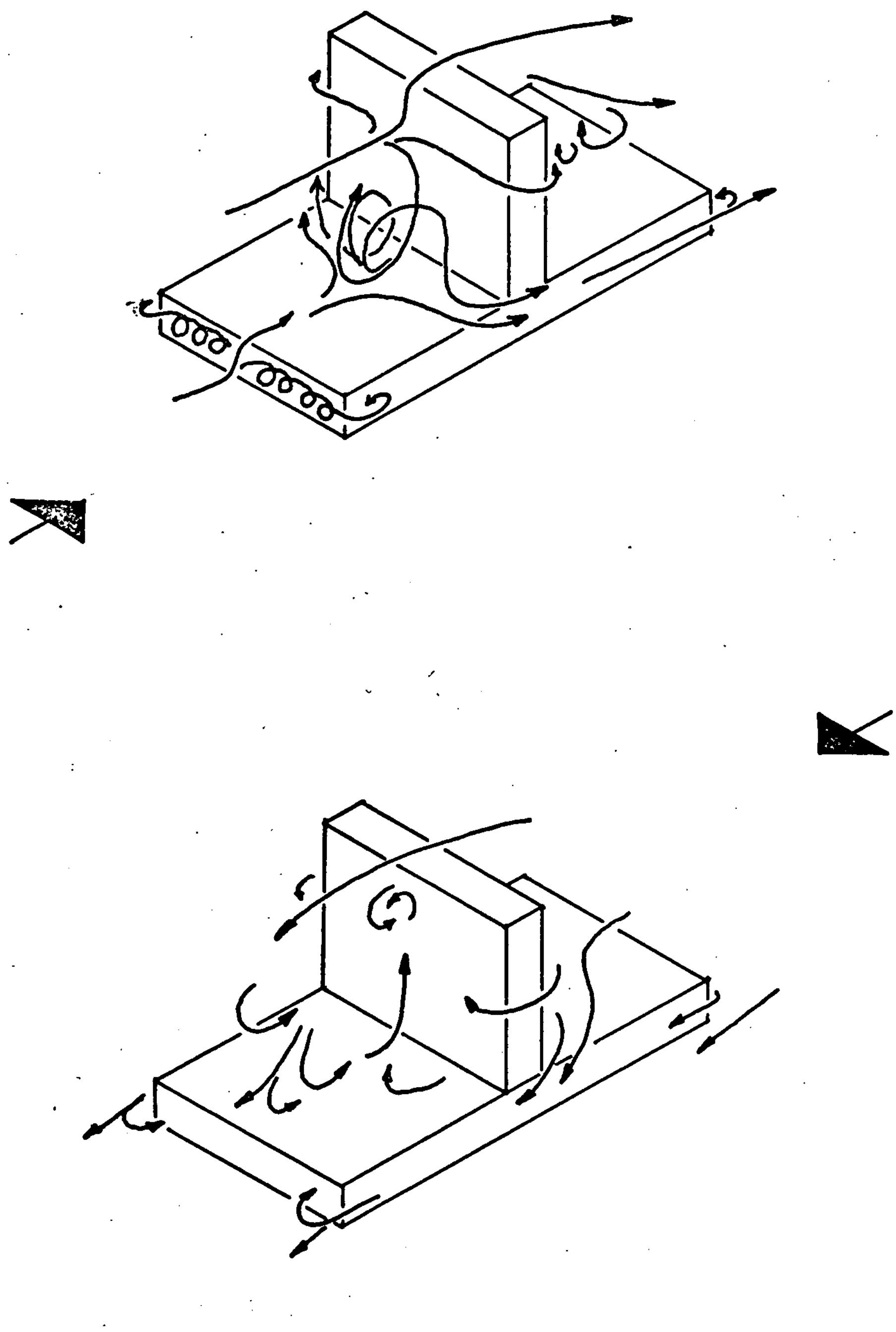
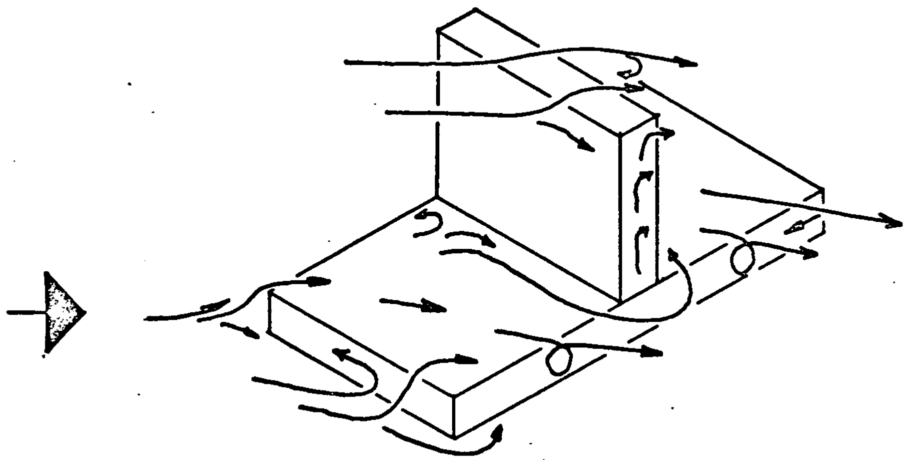


FIG 110 : GEOM 4 : WIND 0°



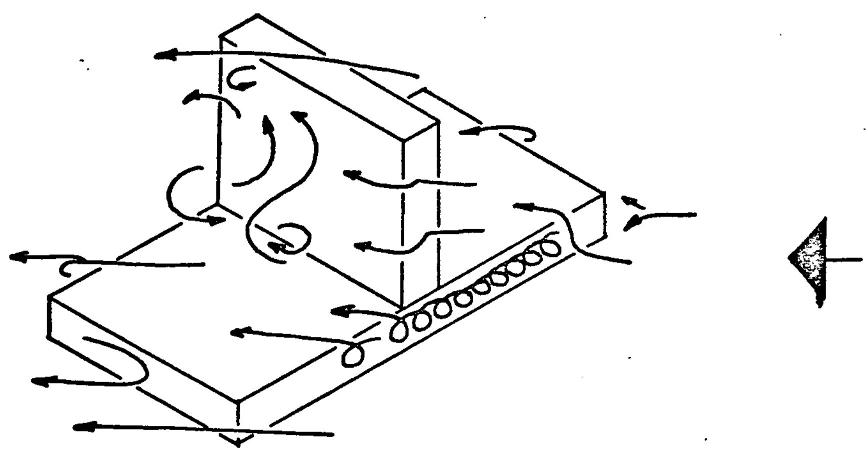


FIG III : GEOM 4 : WIND 135°, 315°

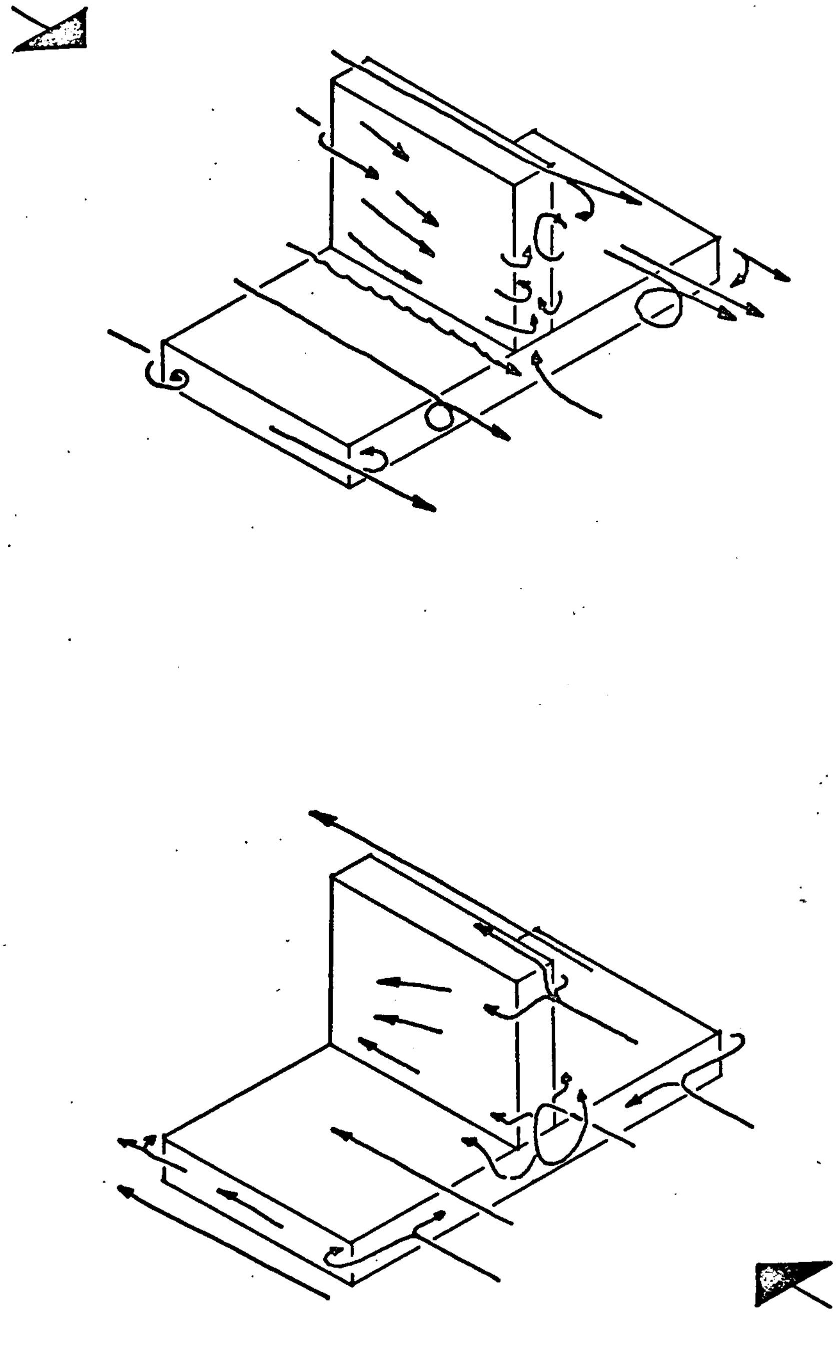


FIG 112 : GEOM 4 : WIND 90°, 270°

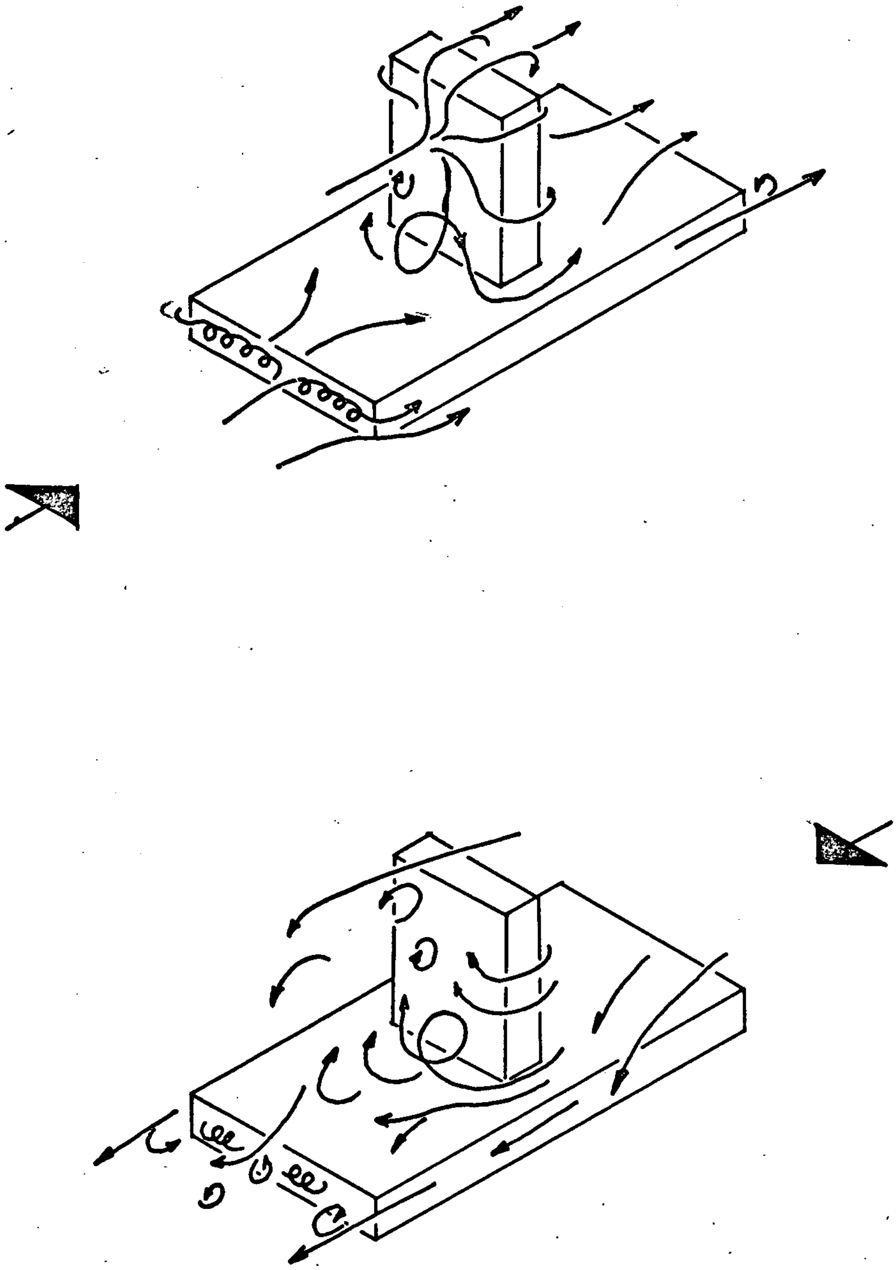
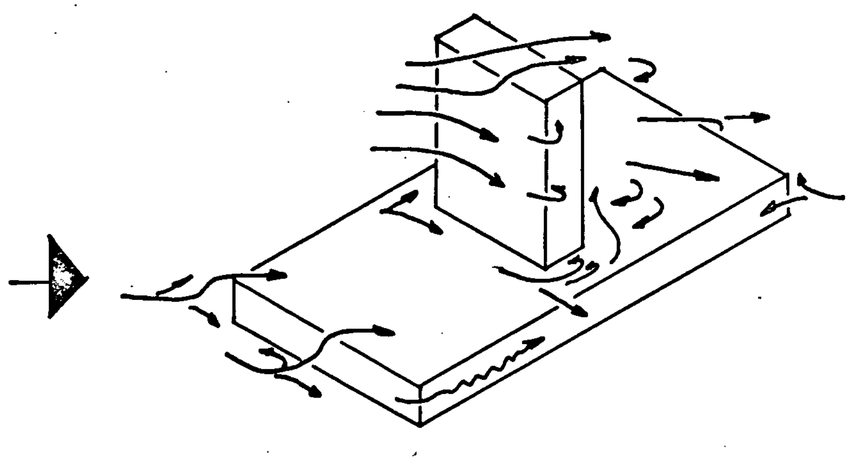


FIG 113 : GEOM 5 : WIND 0°



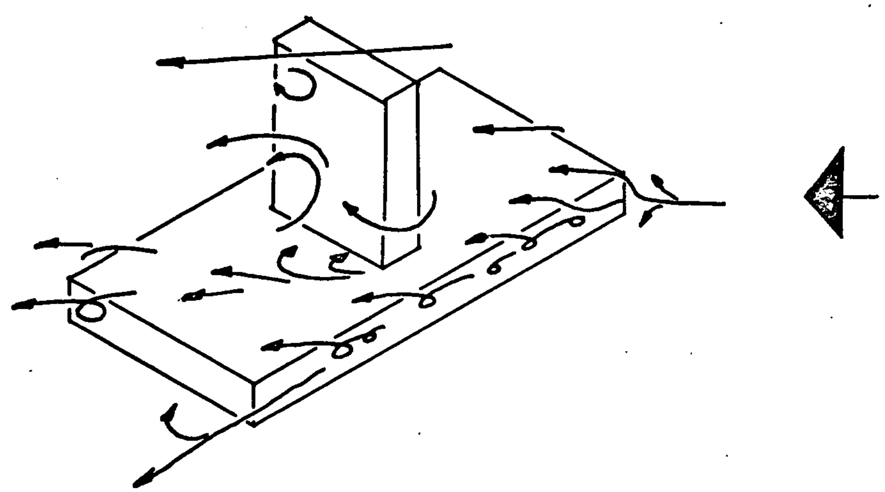
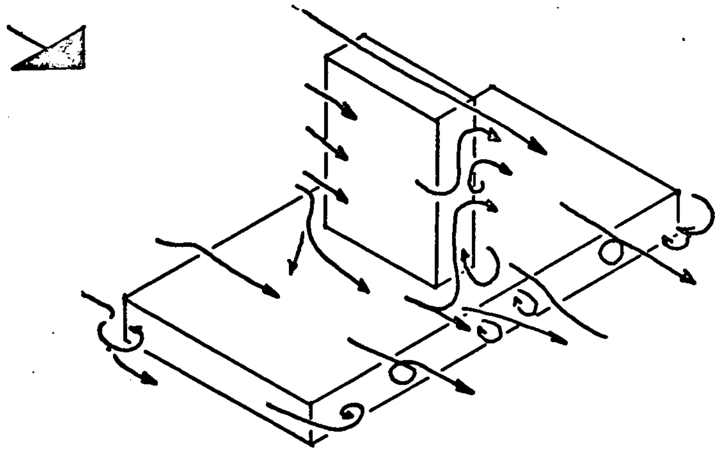


FIG 114 : GEOM 5 : WIND 315°



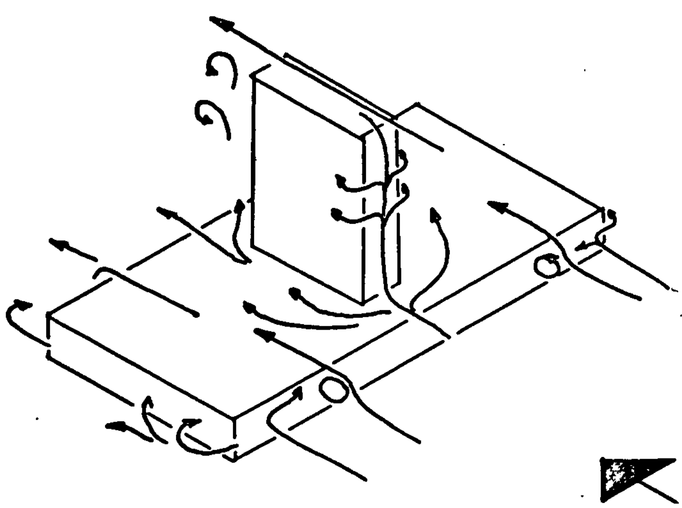


FIG 115 : GEOM 5 : WIND 270°

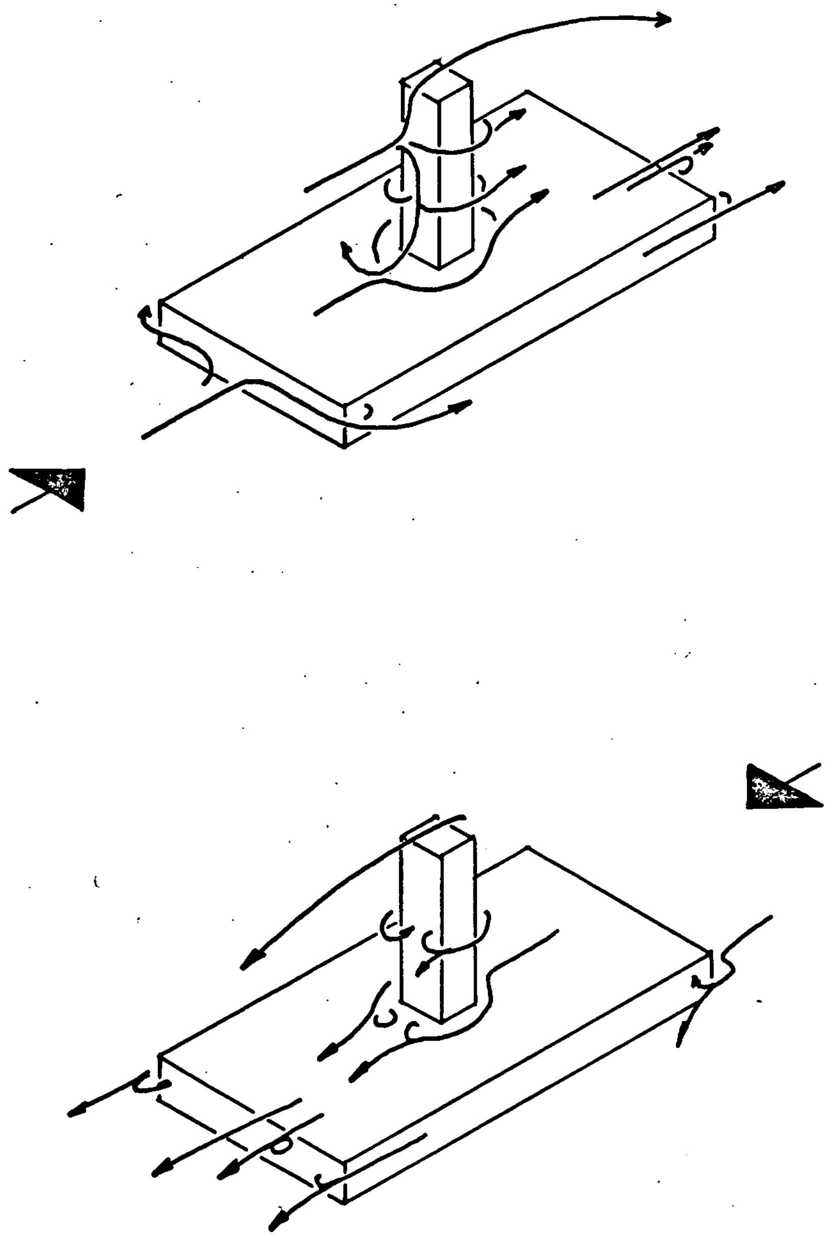


FIG 116 : GEOM 6 : WIND 0°

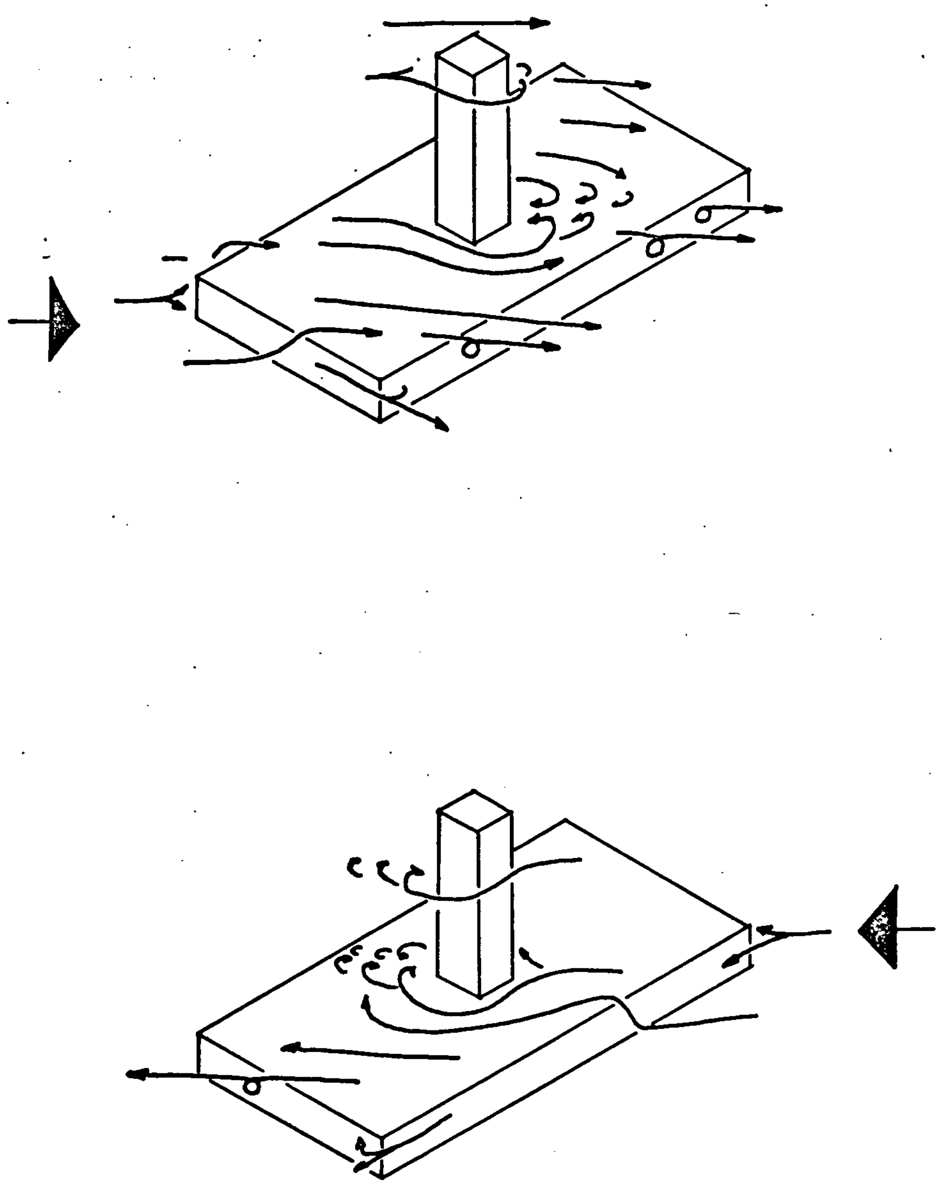


FIG 117 : GEOM 6 : WIND 315°

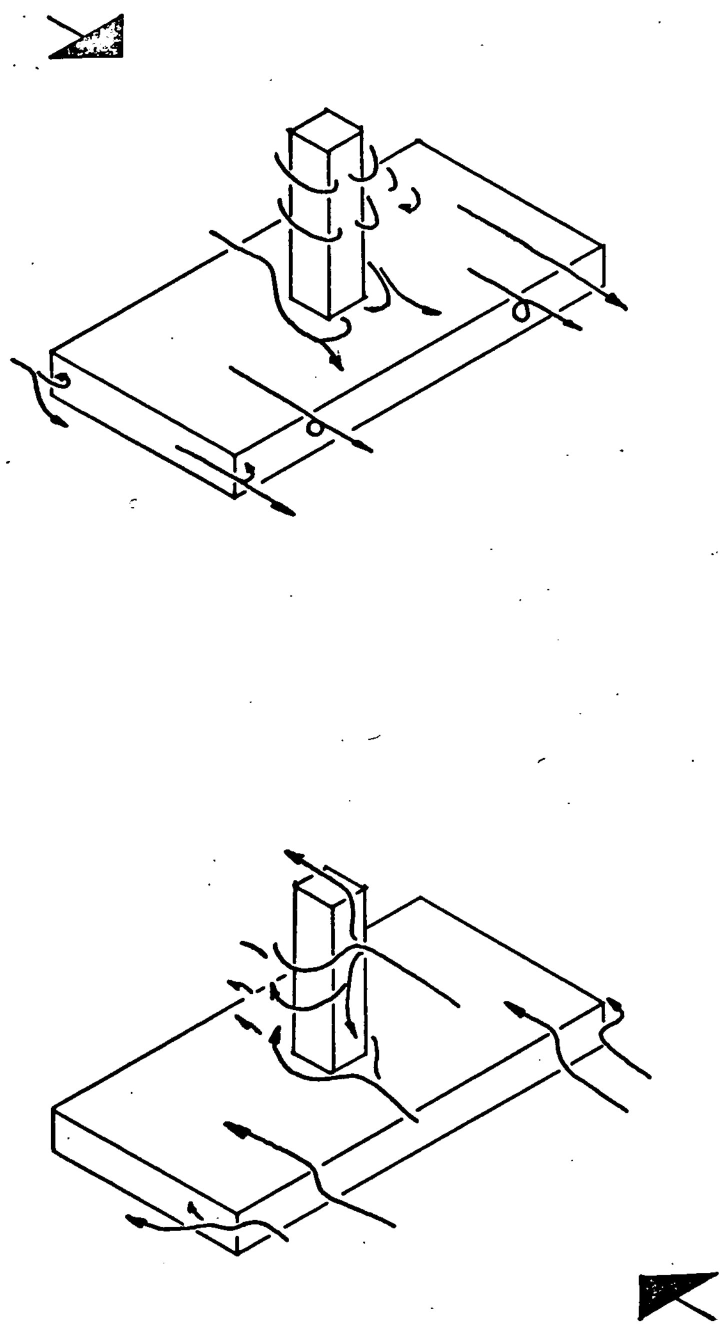


FIG 118 : GEOM 6 : WIND 270°

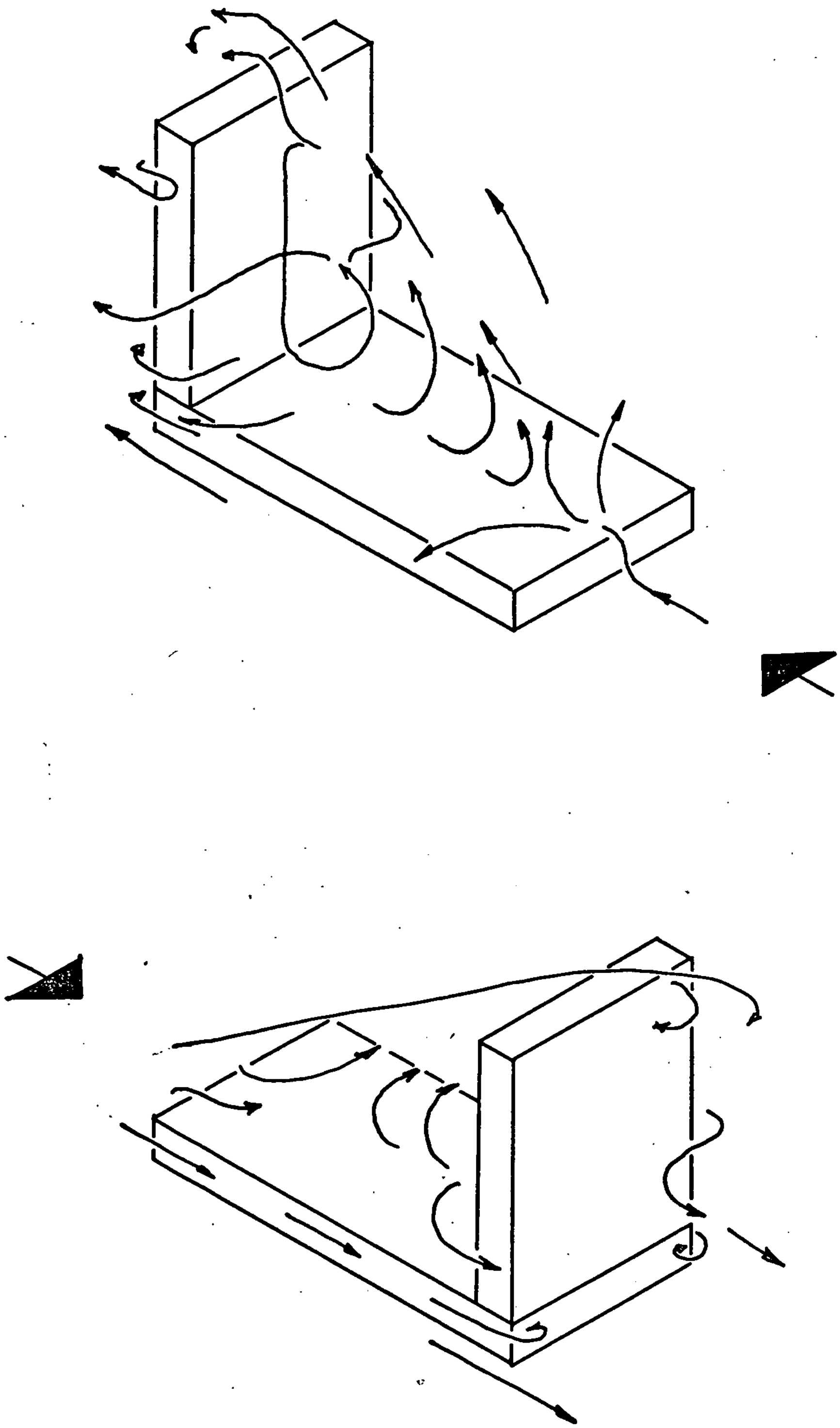


FIG 119 : GEOM 7 : WIND 0°

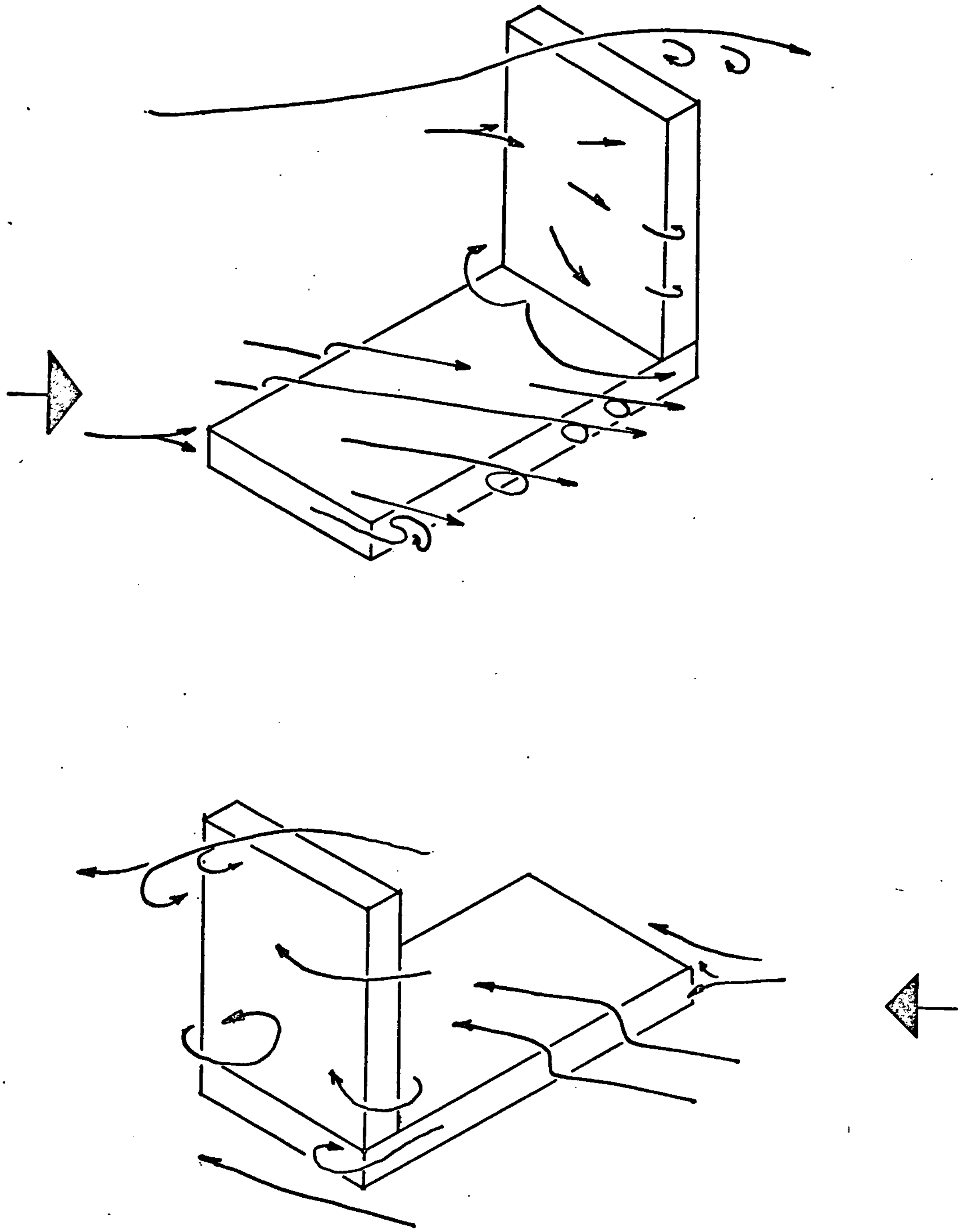


FIG 120 : GEOM 7 : WIND 315°

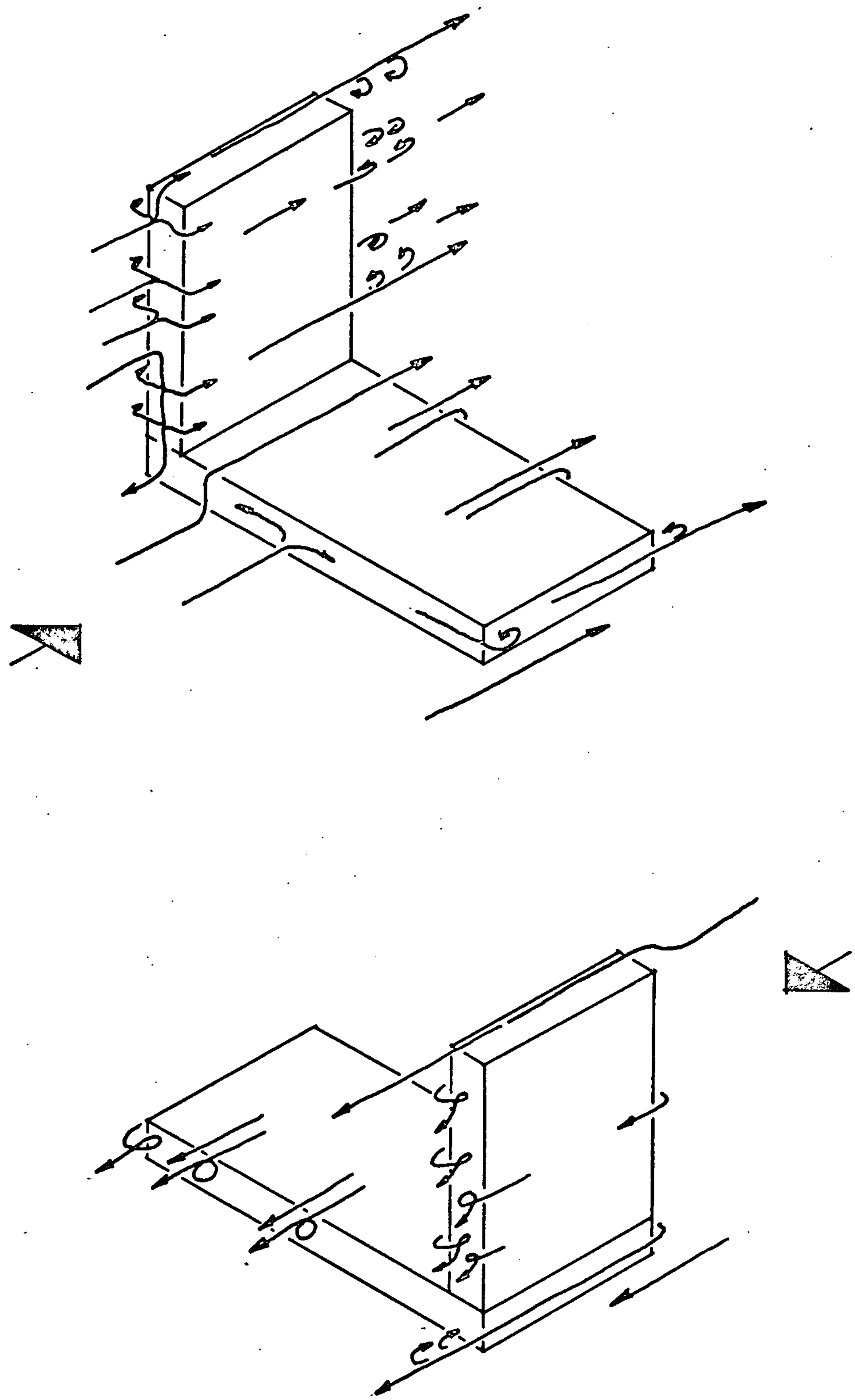


FIG 121 : GEOM 7 : WIND 270°

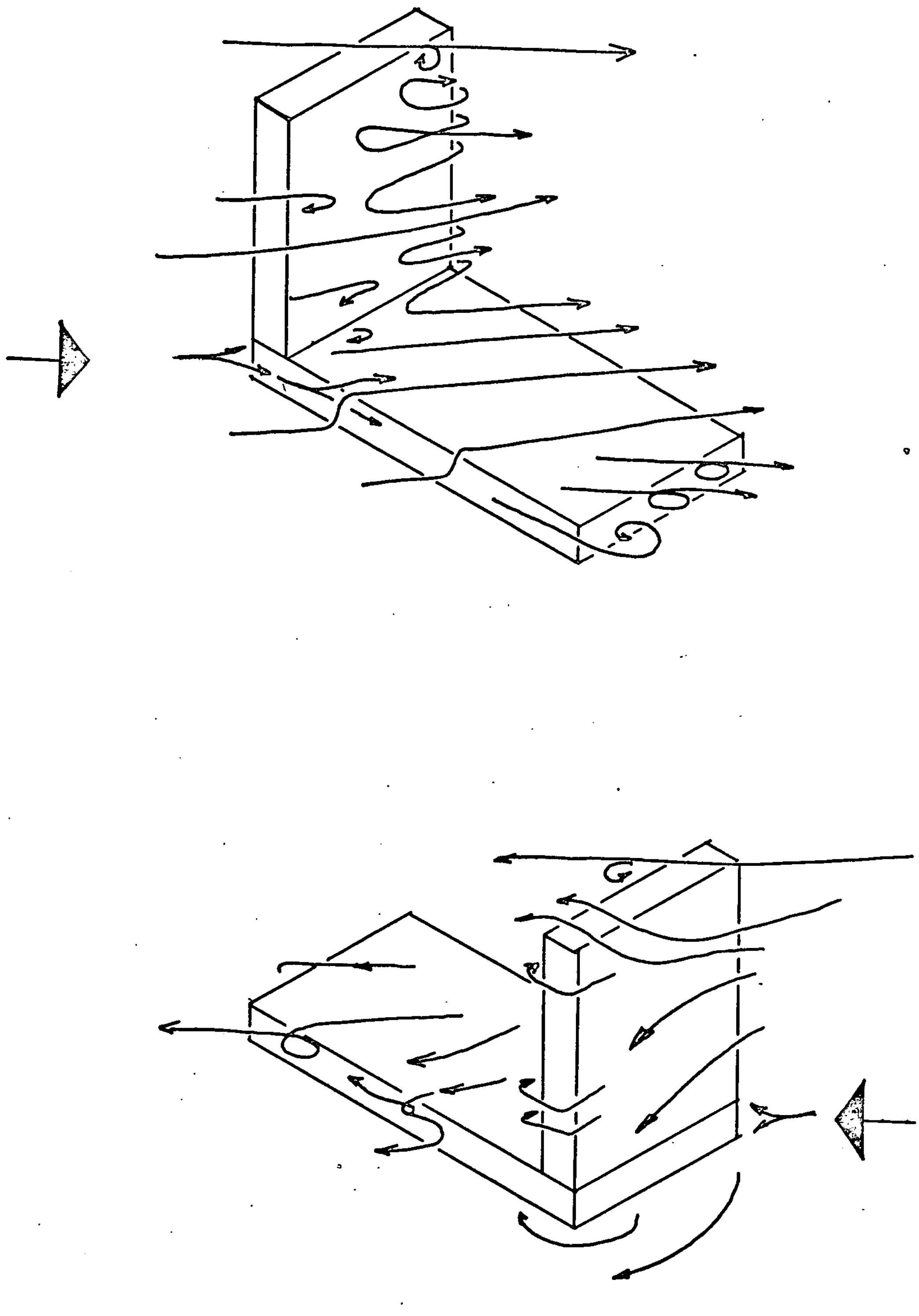


FIG 122 : GEOM 7 : WIND 225°

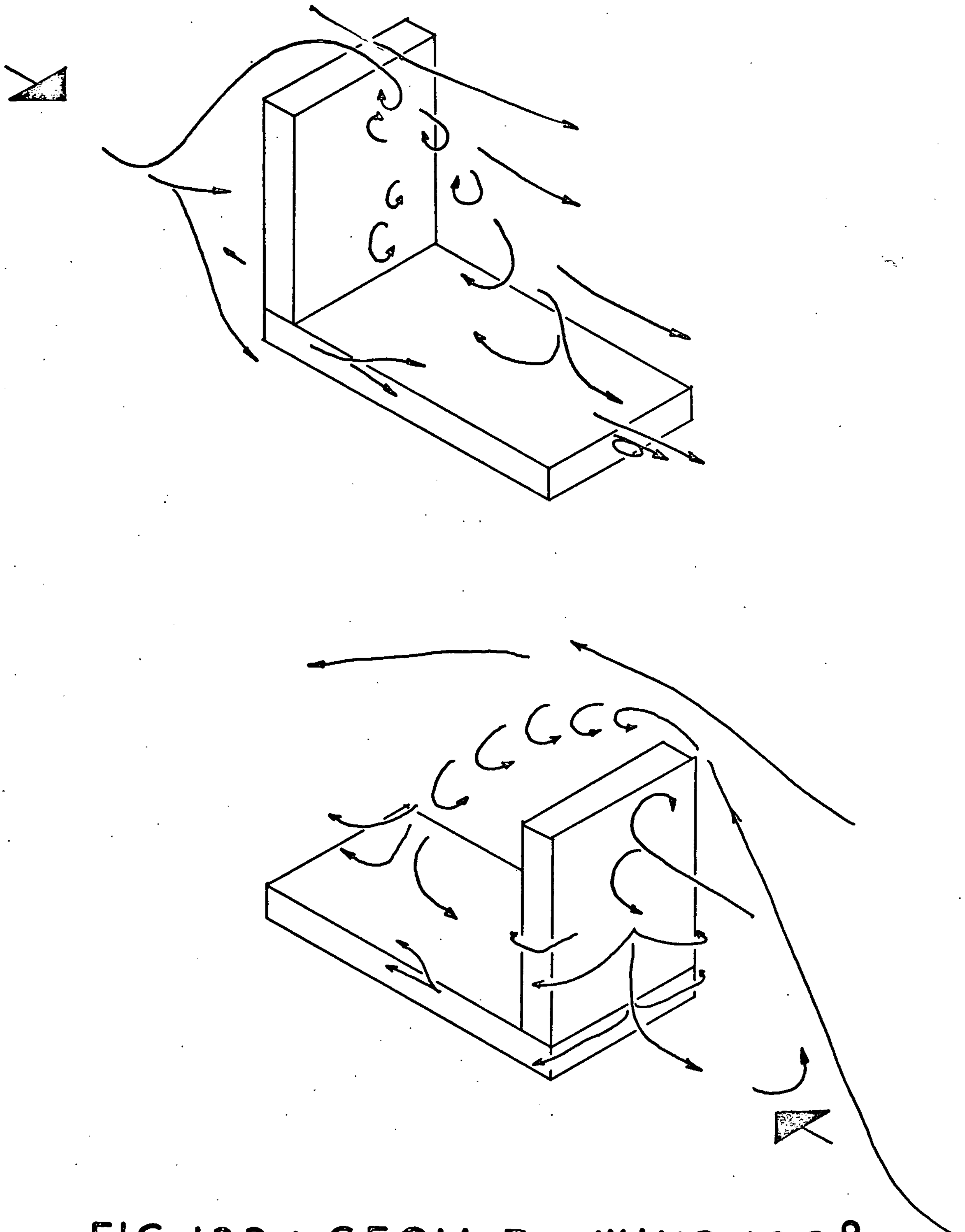
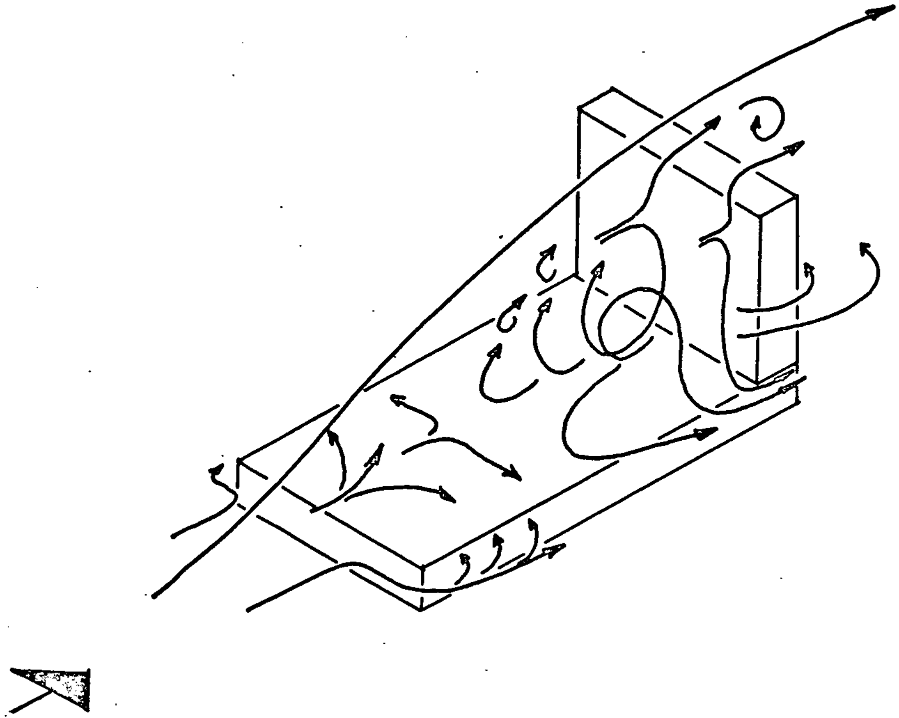


FIG 123 : GEOM 7 : WIND 180°



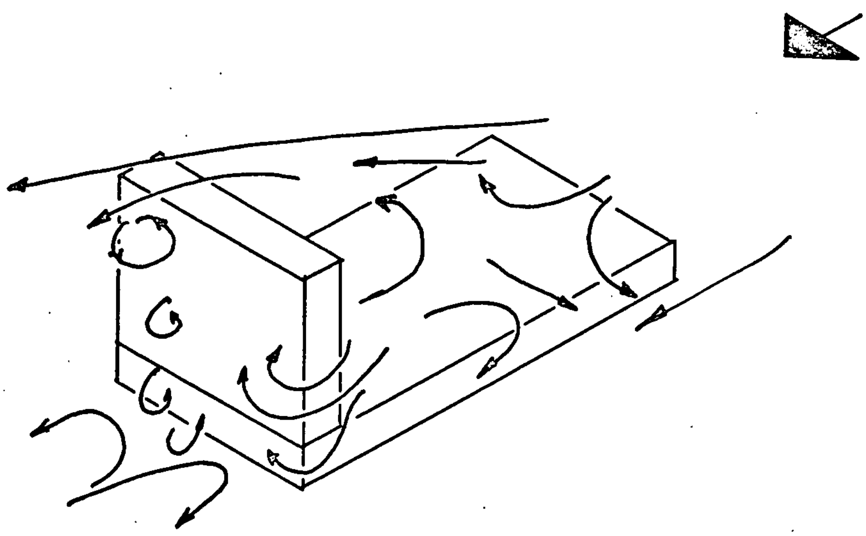
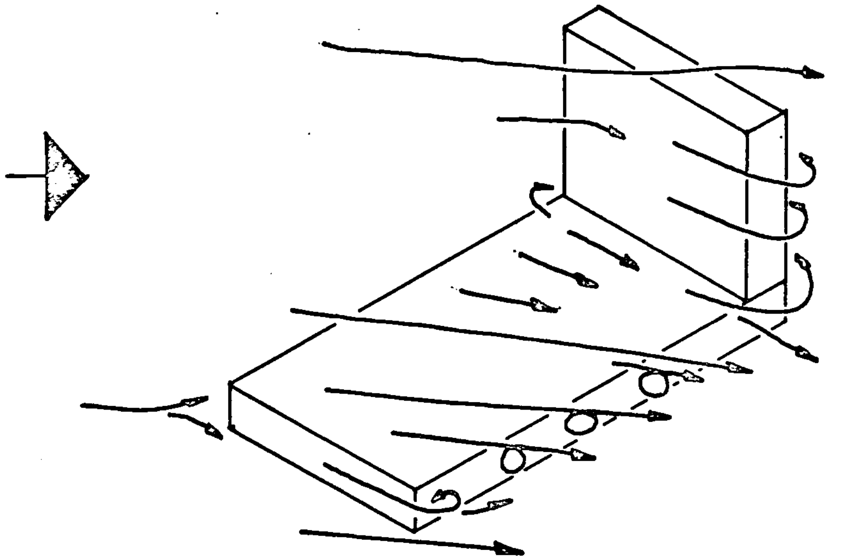


FIG 124 : GEOM 8 : WIND 0°



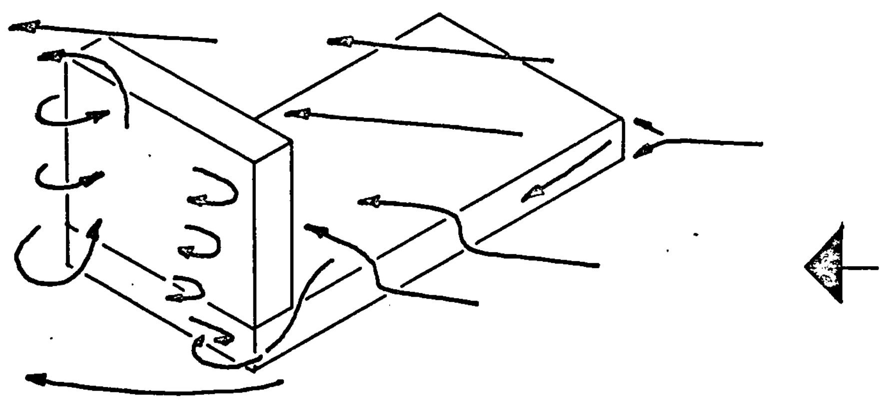


FIG 125 : GEOM 8 : WIND 315°

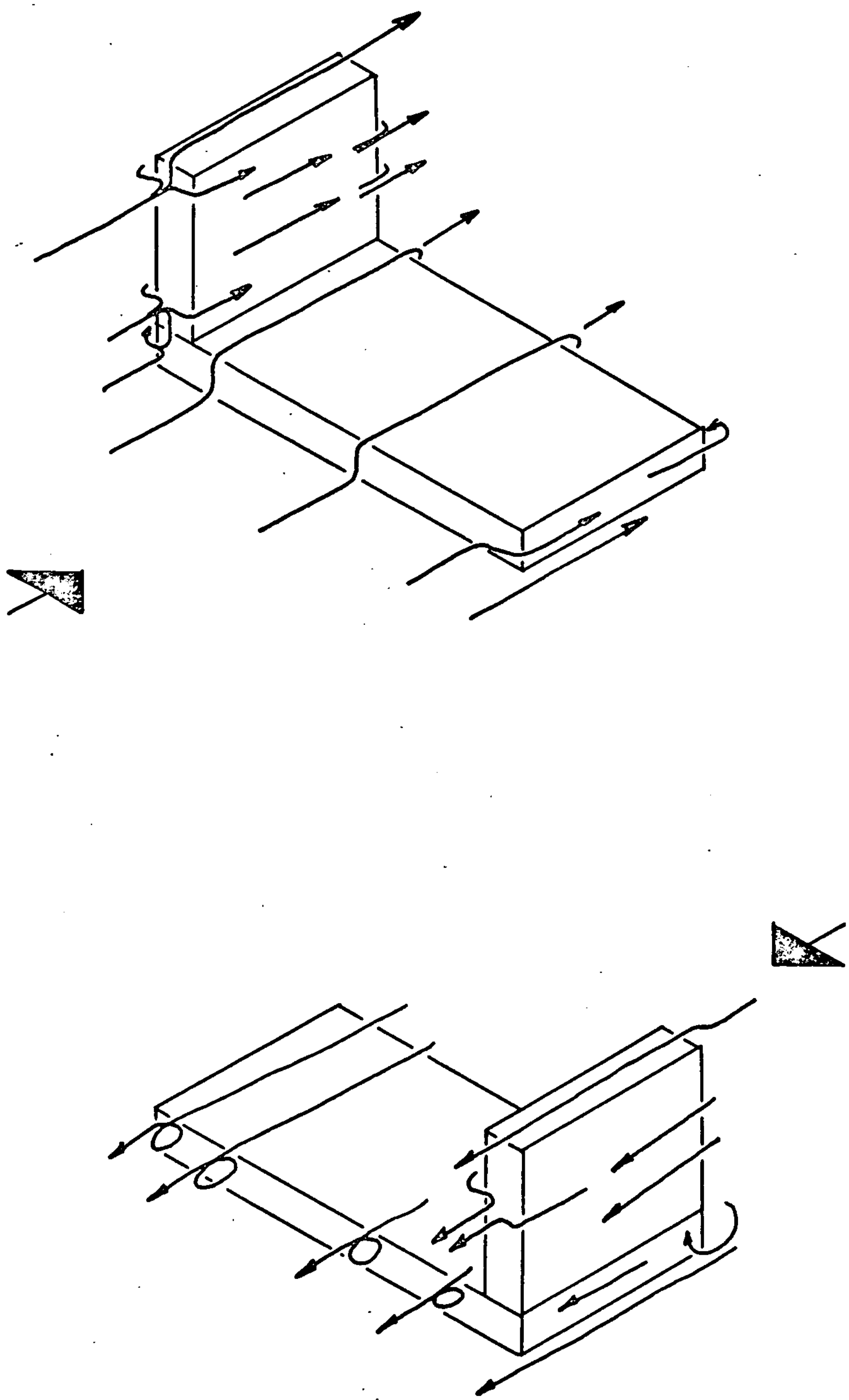


FIG 126 : GEOM 8 : WIND 270°

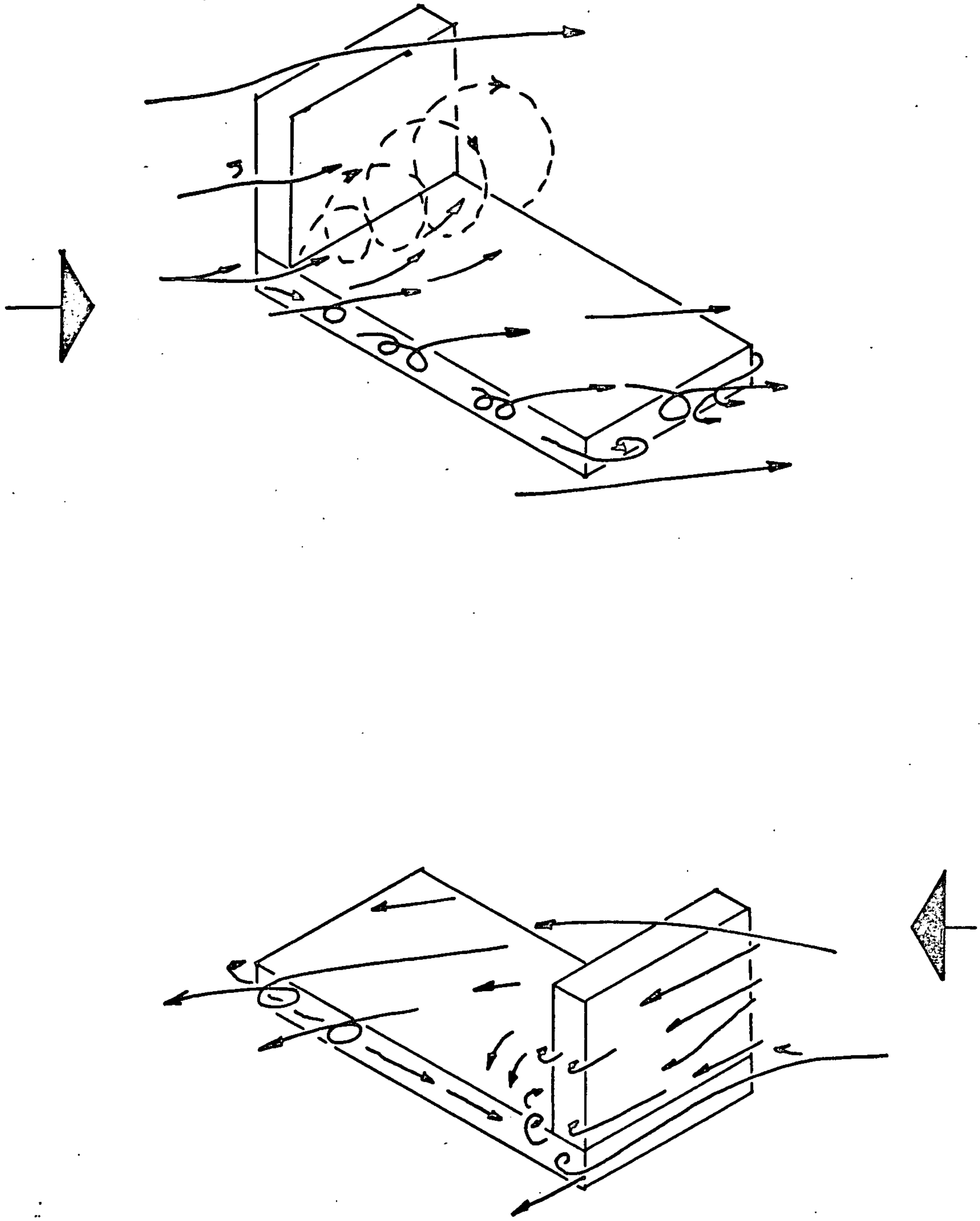
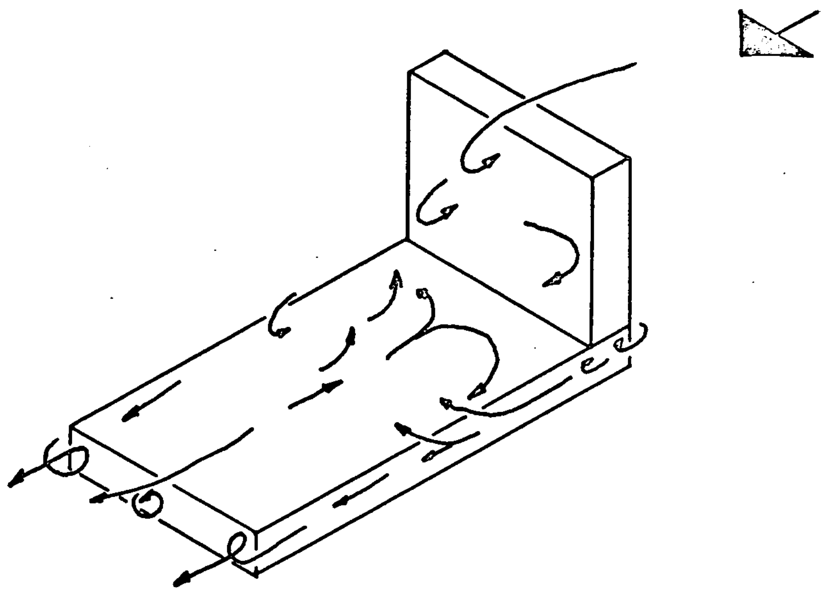


FIG 127 : GEOM 8 : WIND 225°



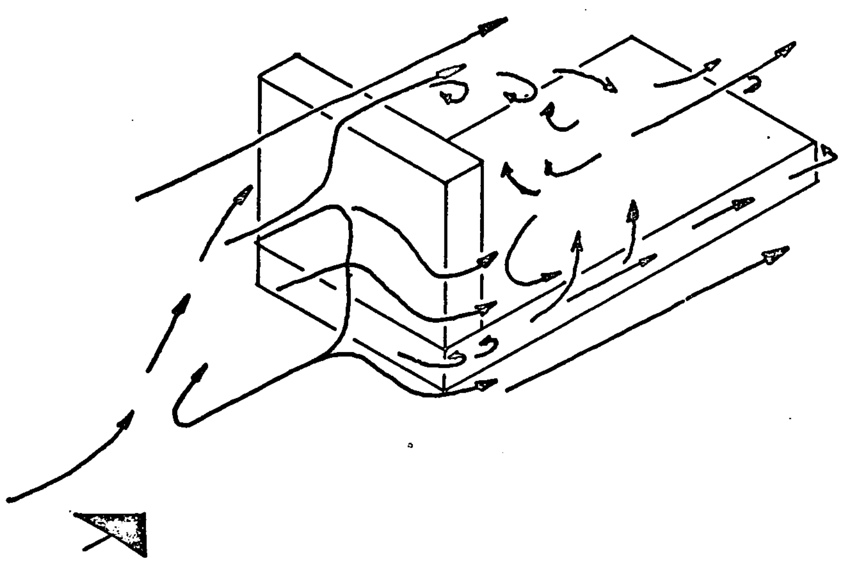


FIG 128 : GEOM 8 : WIND 180°

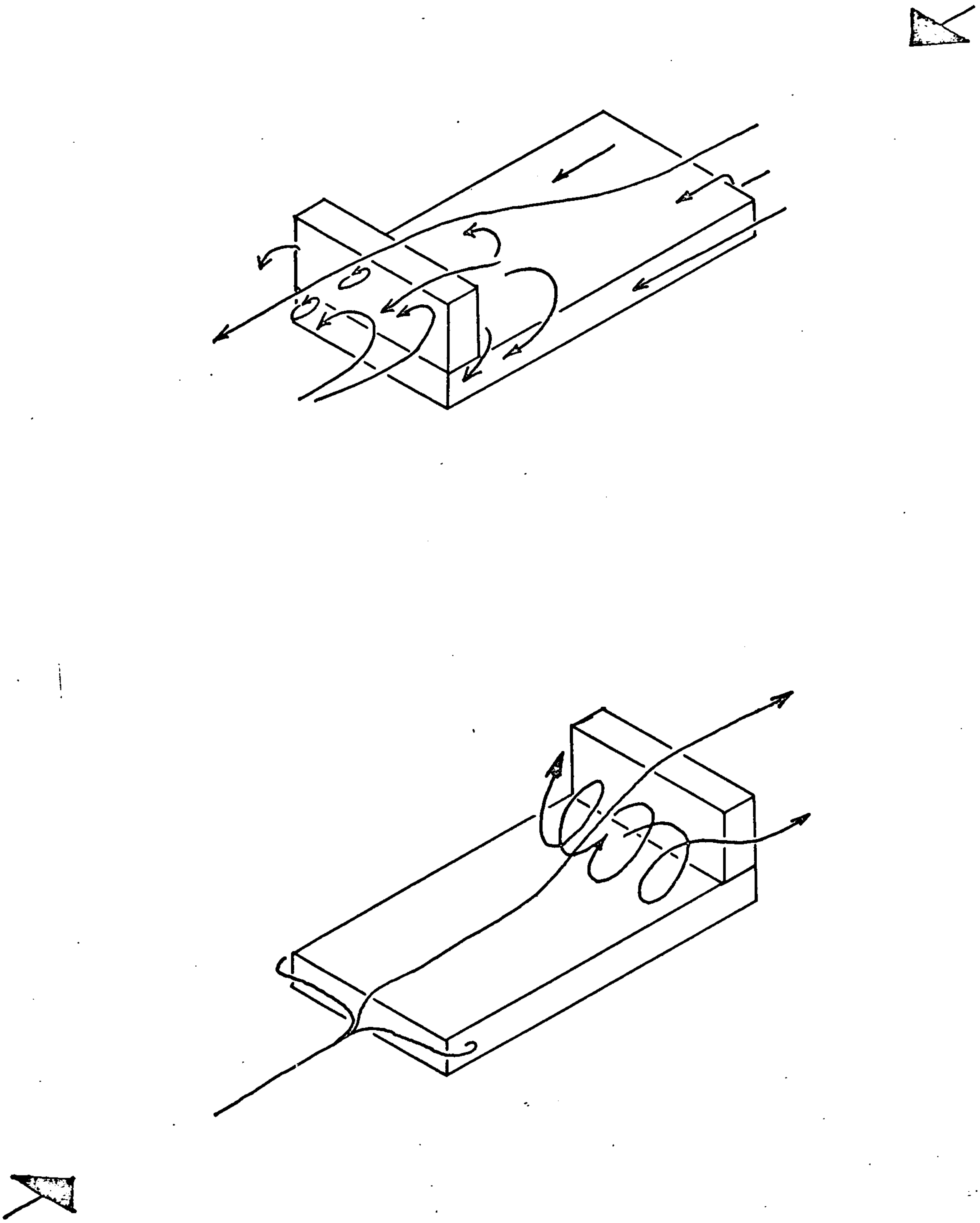


FIG 129 : GEOM 9 : WIND 0°

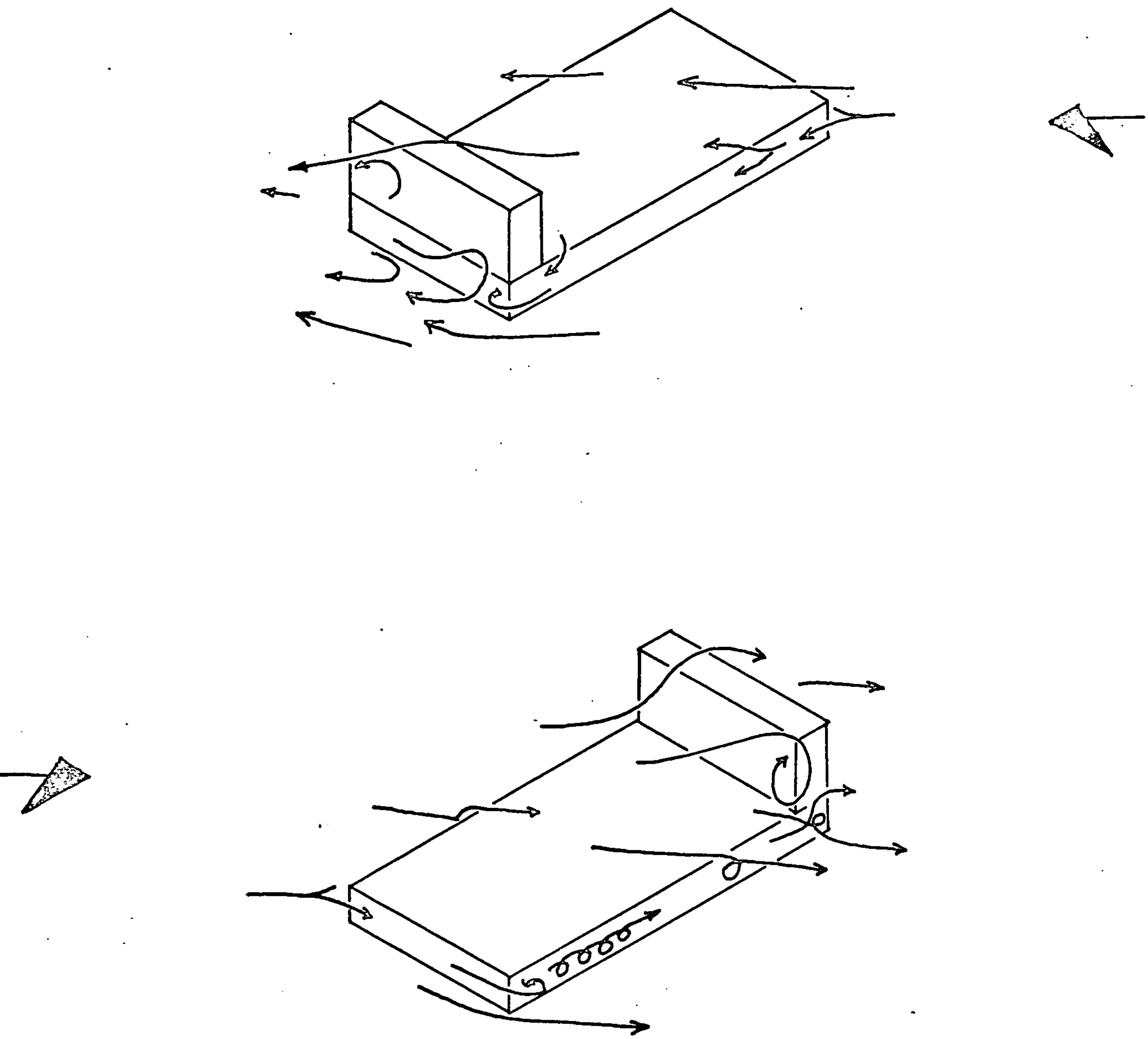


FIG 130 : GEOM 9 : WIND 315°

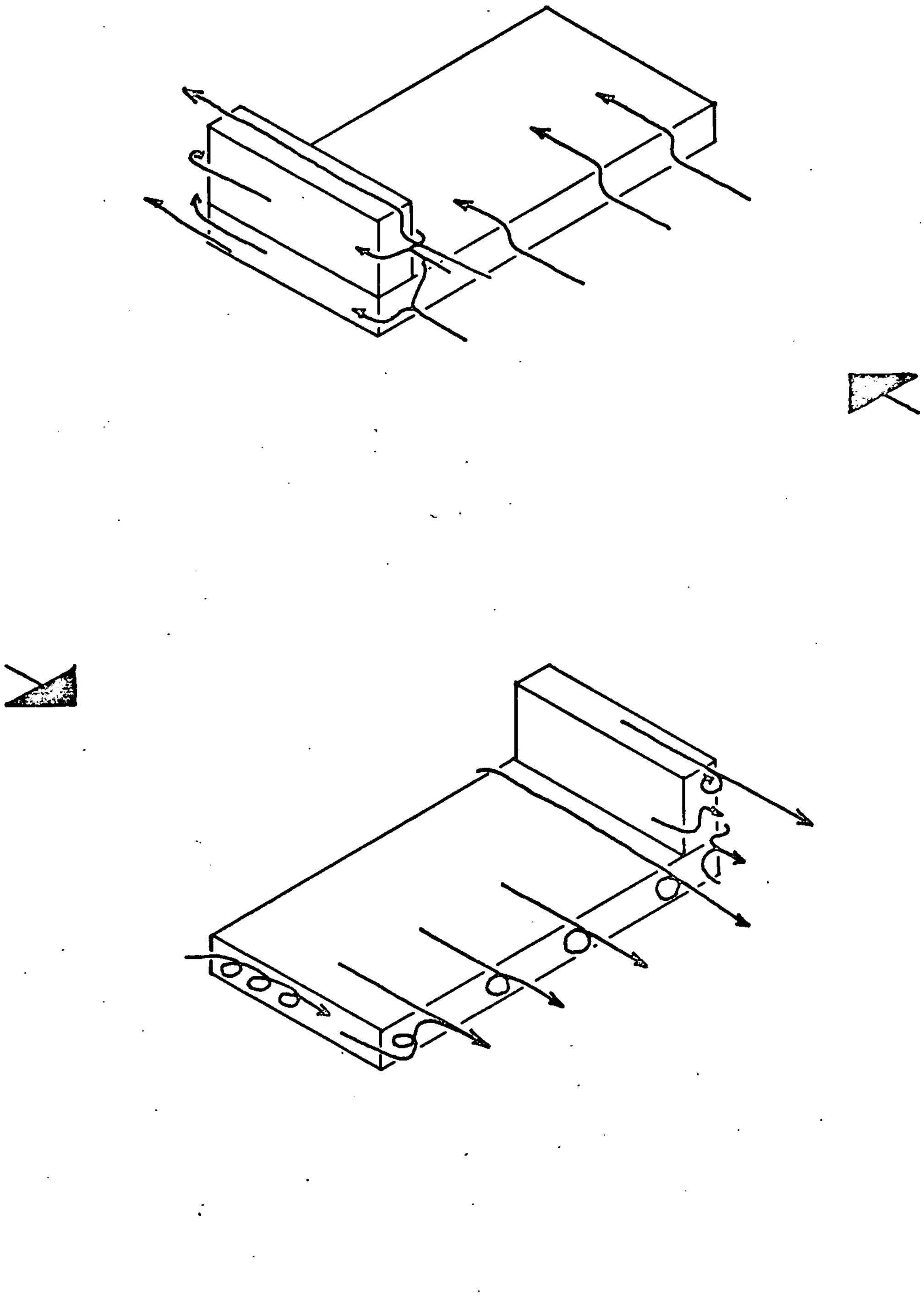


FIG 131 : GEOM 9 : WIND 270°

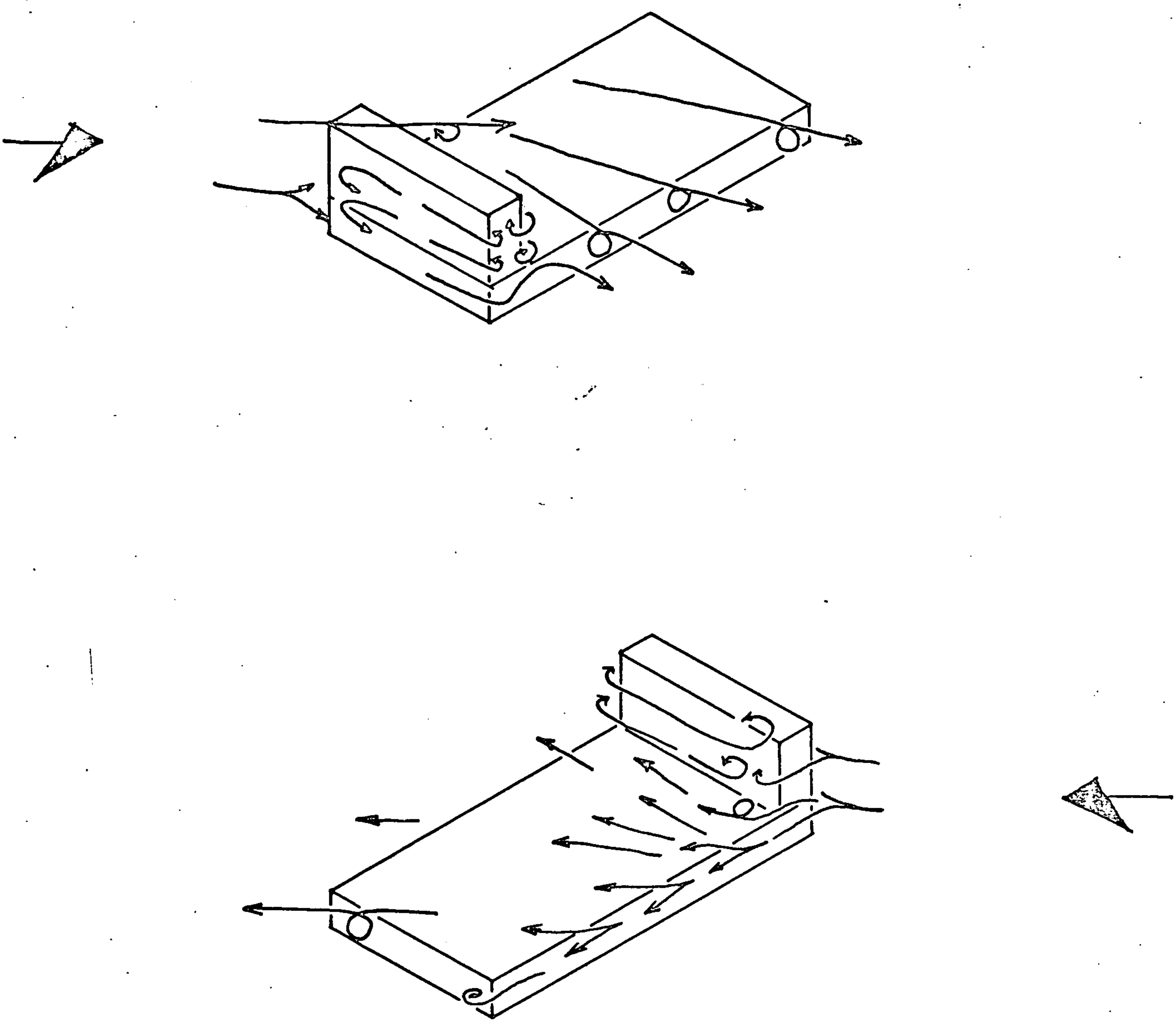
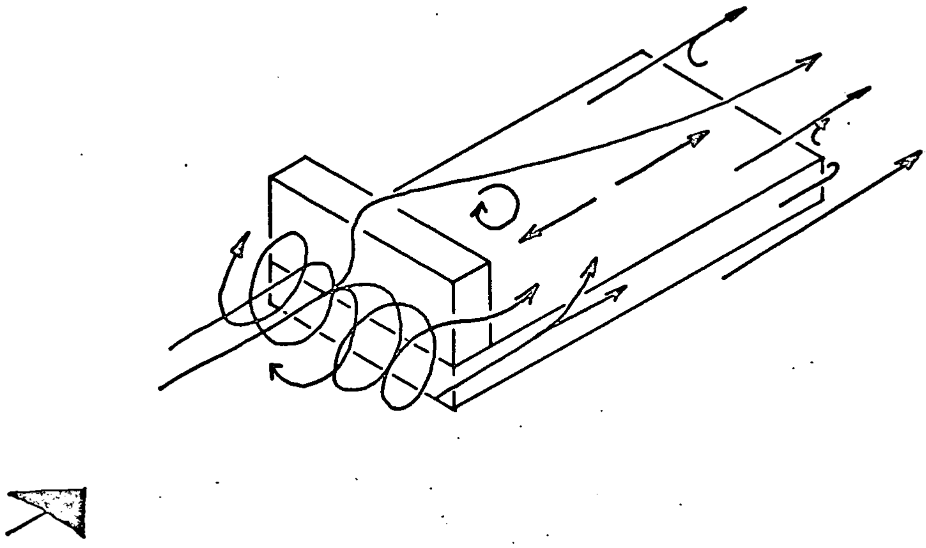


FIG 132 : GEOM 9 : WIND 225°



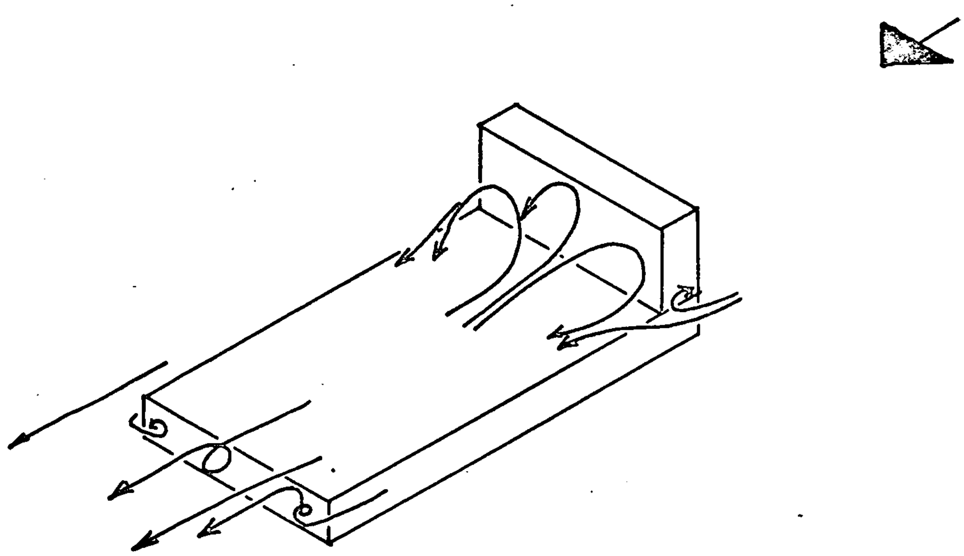


FIG 133 : GEOM 9 : WIND 180°

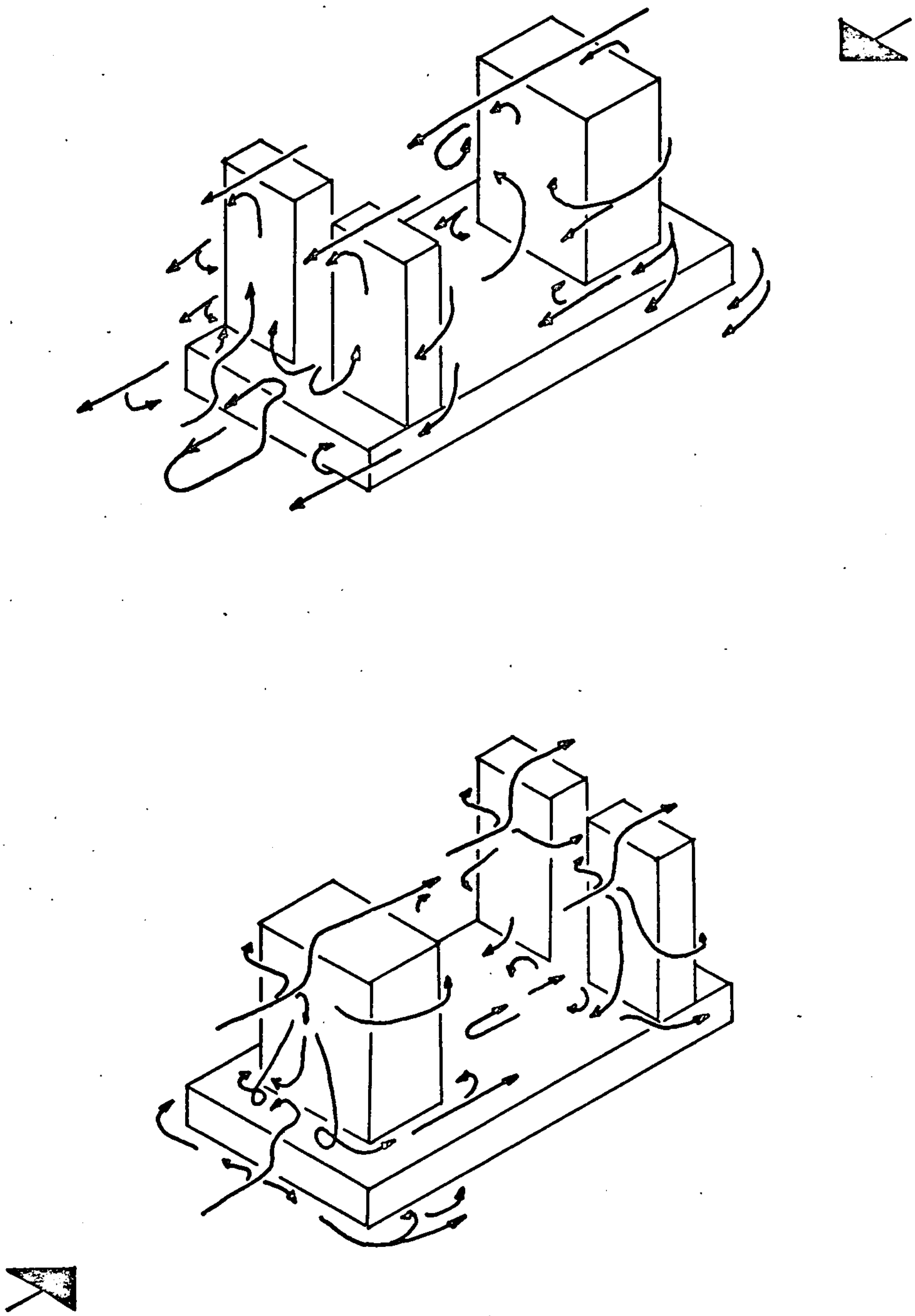


FIG 134 : GEOM 10 : WIND 0°

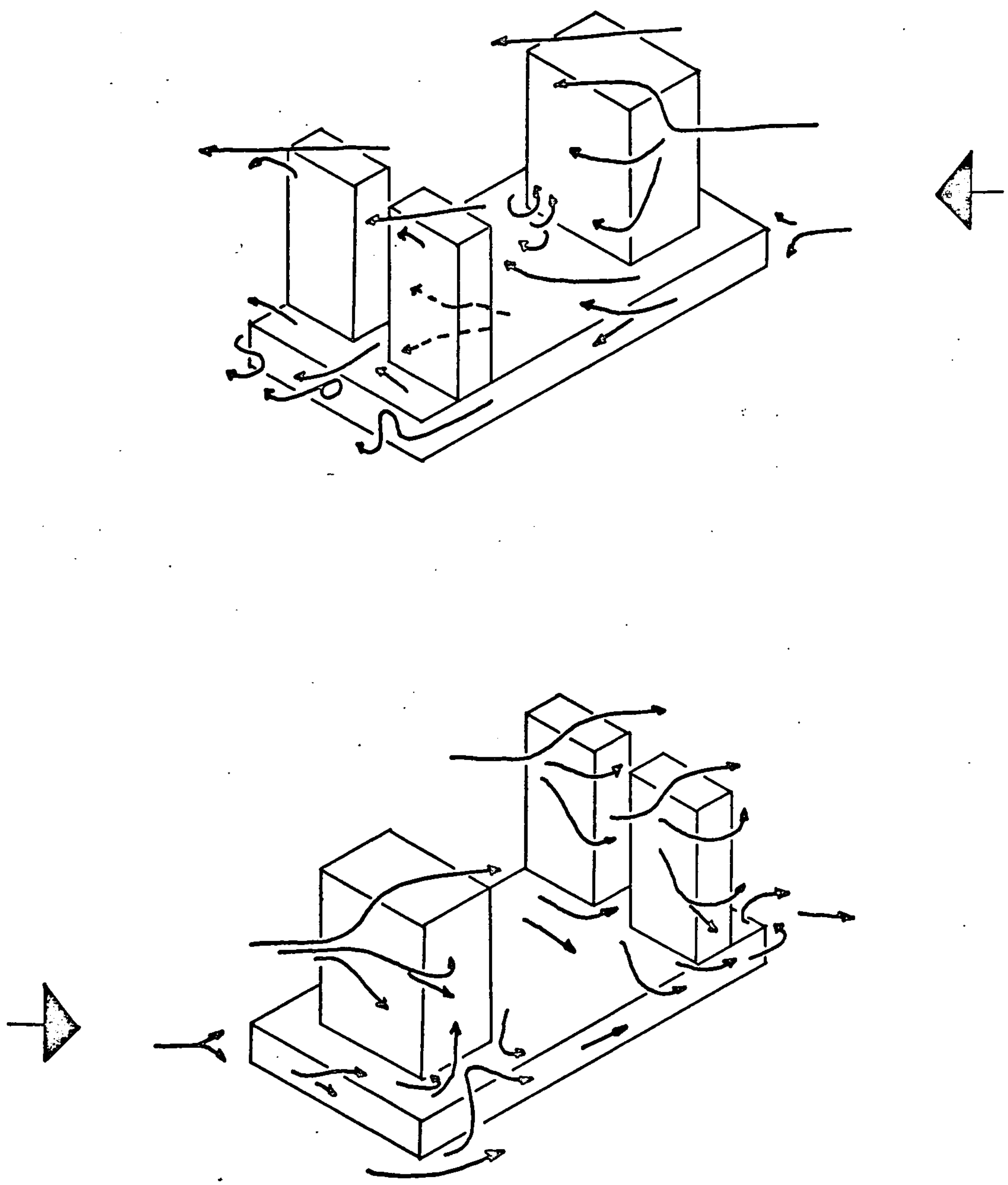
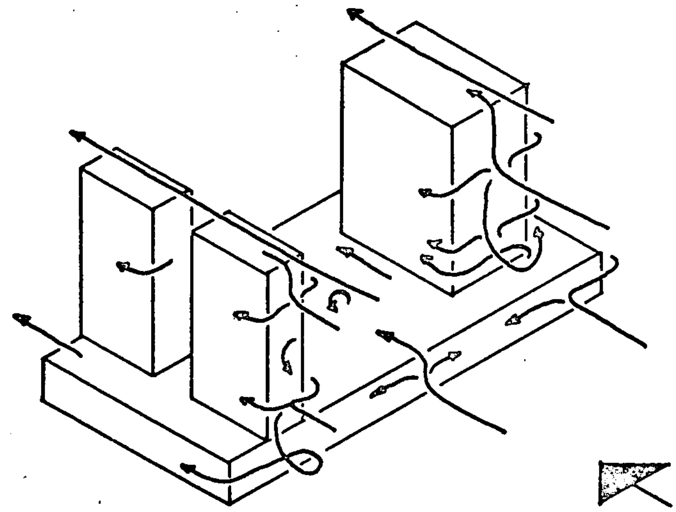


FIG 135 : GEOM 10 : WIND 315°



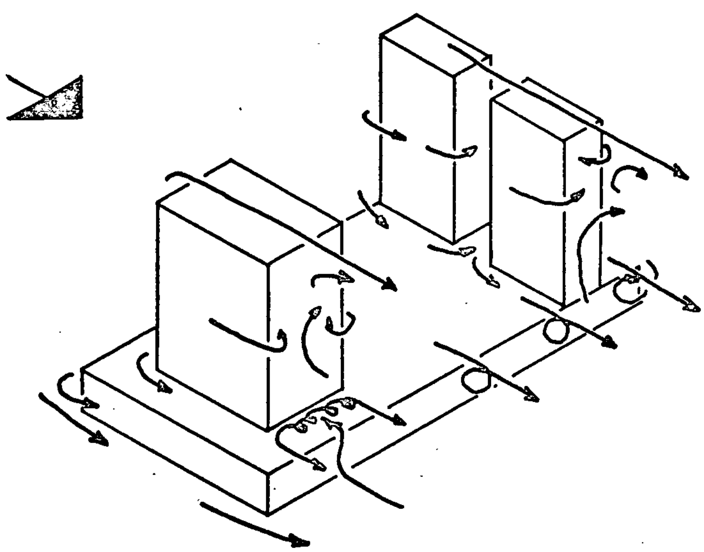
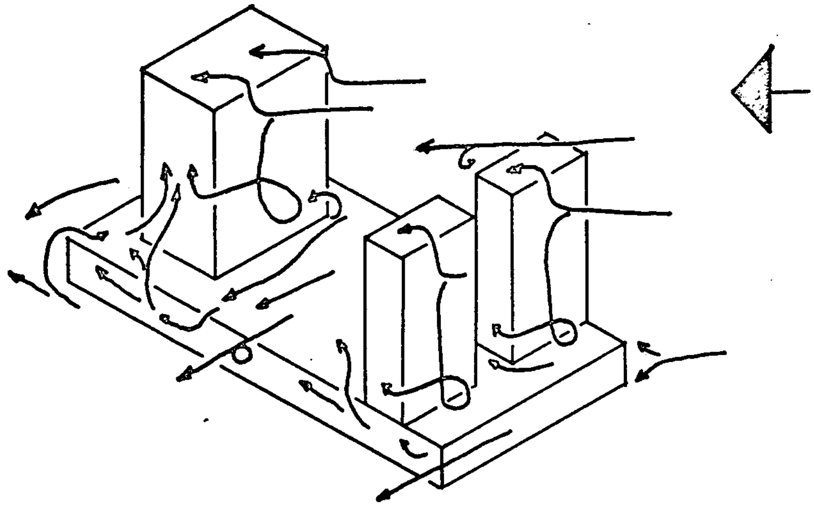


FIG 136 : GEOM 10 : WIND 270°



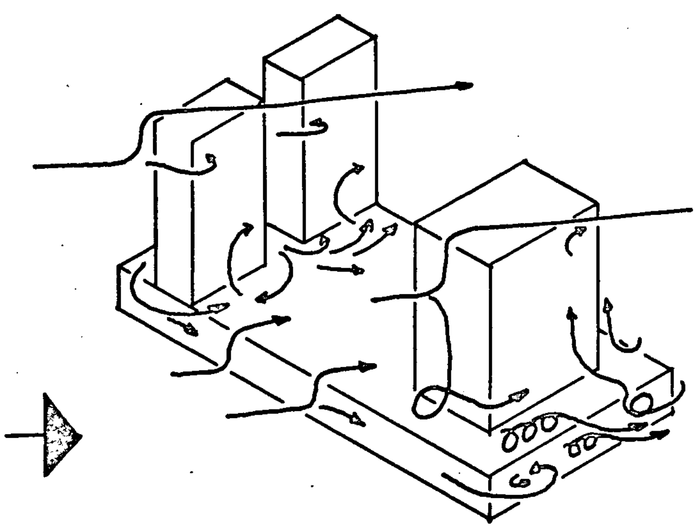
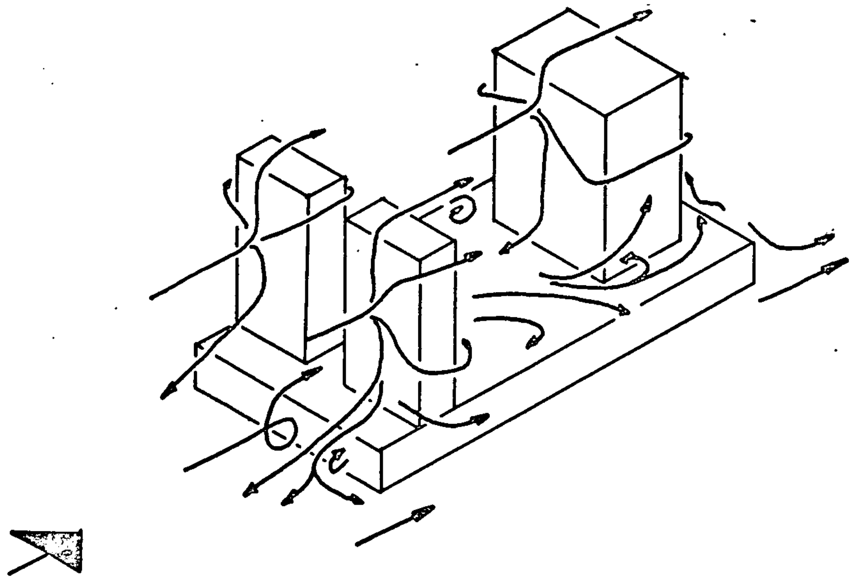


FIG 137 : GEOM 10 : WIND 225°



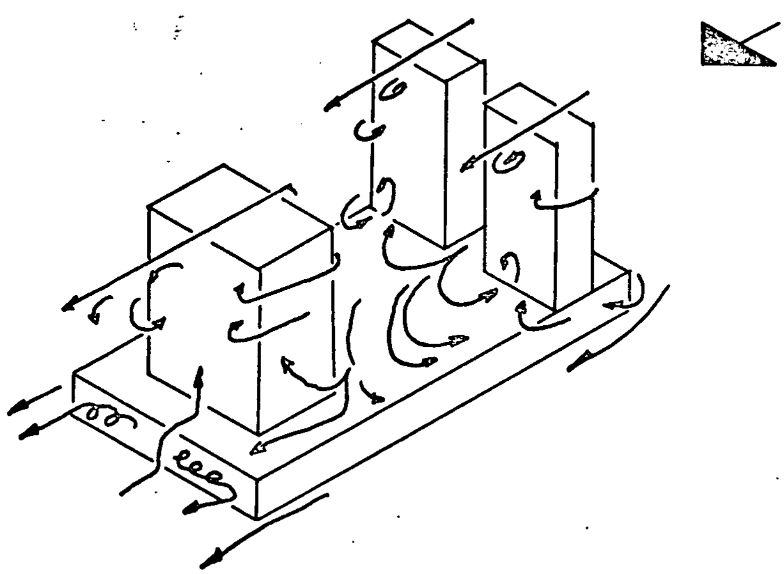


FIG 138 : GEOM 10 : WIND 180°

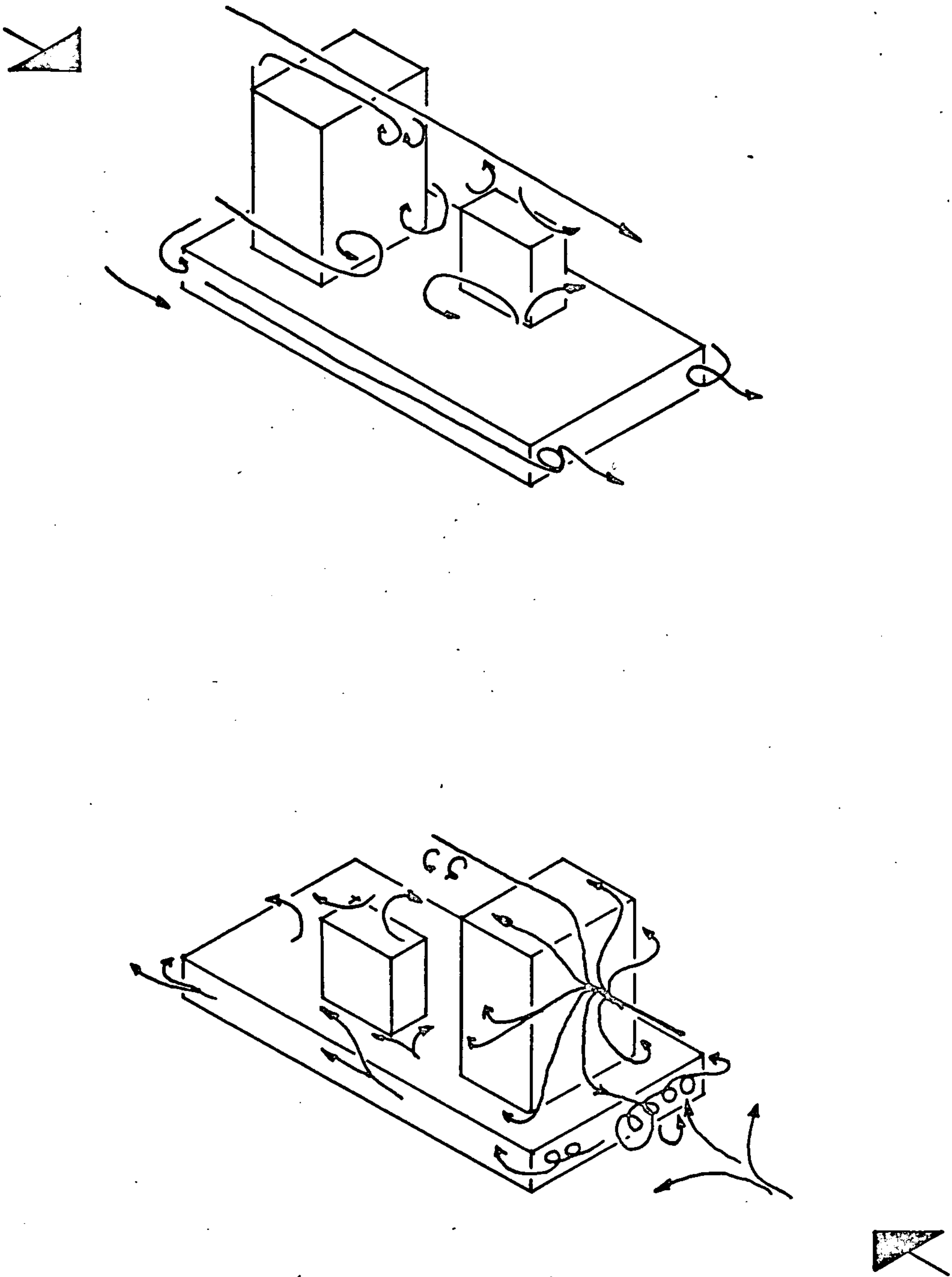


FIG 139 : GEOM II : WIND 0°

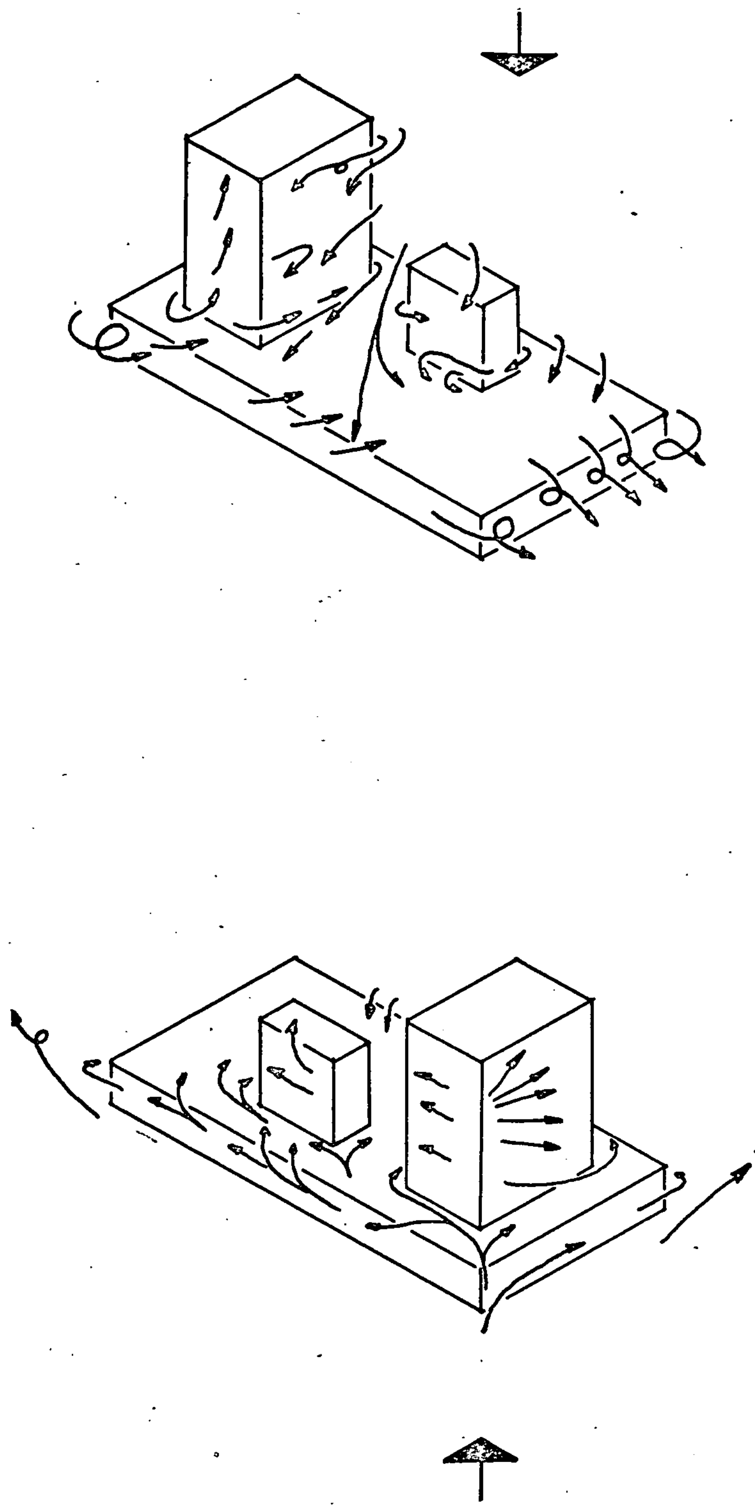
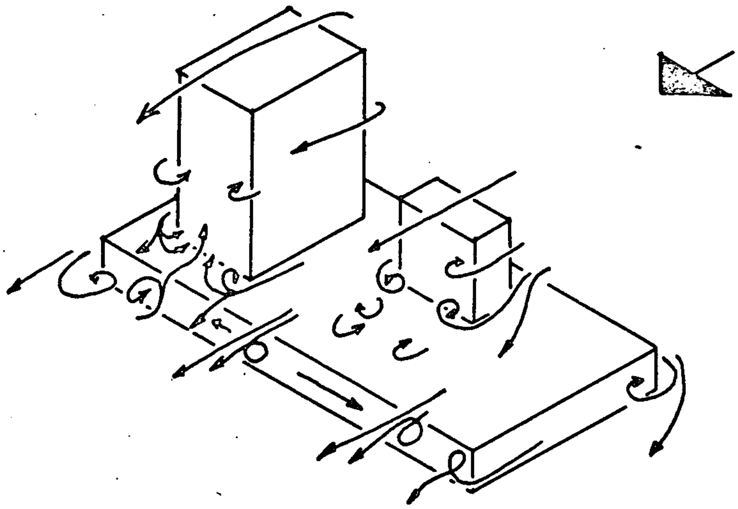


FIG 140 : GEOM II : WIND 315°



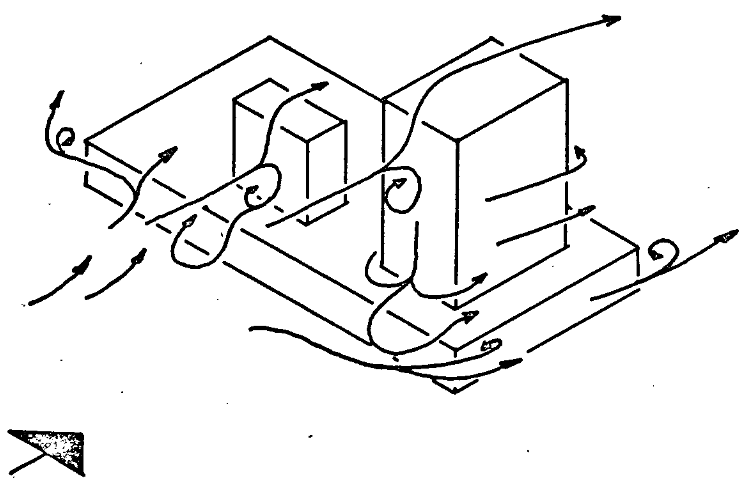
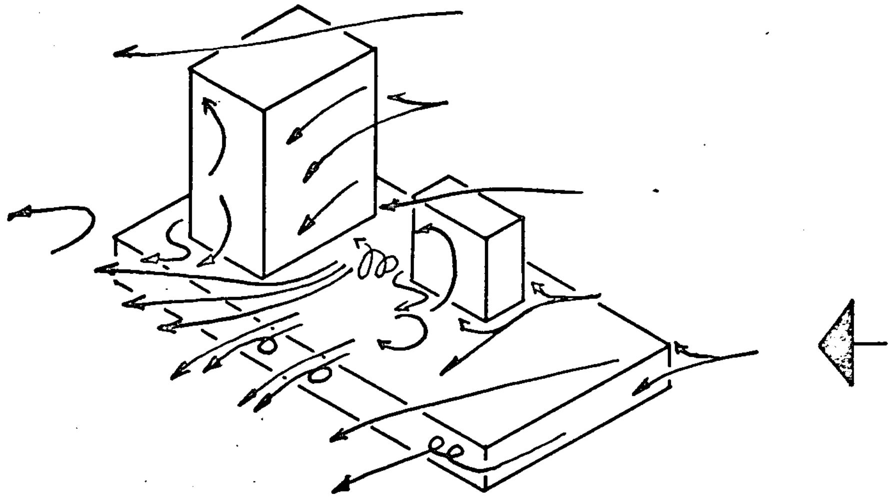


FIG 141 : GEOM II : WIND 270°



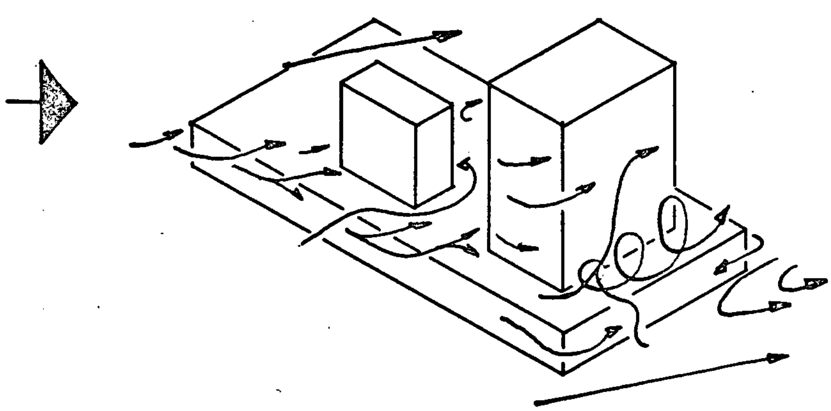
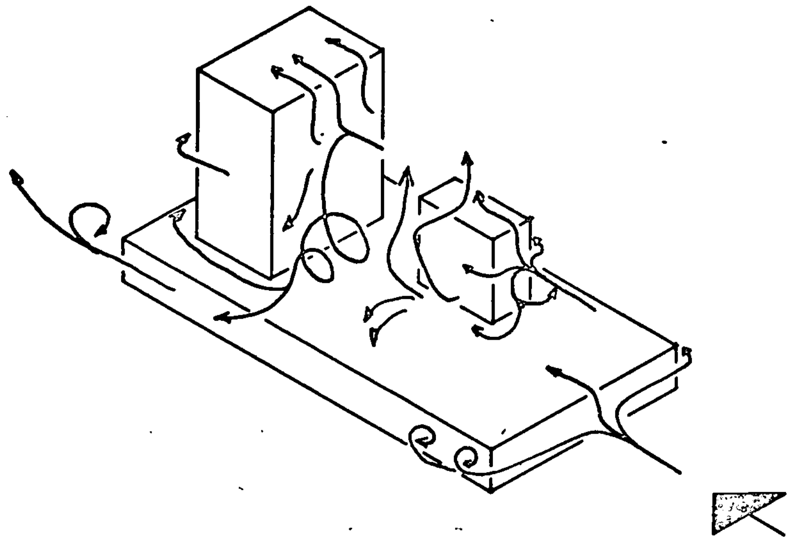


FIG 142 : GEOM II : WIND 225°



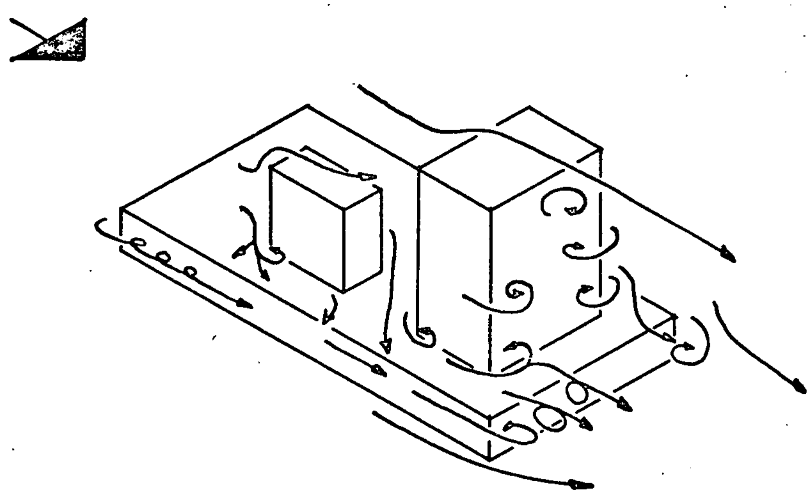


FIG 143 : GEOM II : WIND 180°

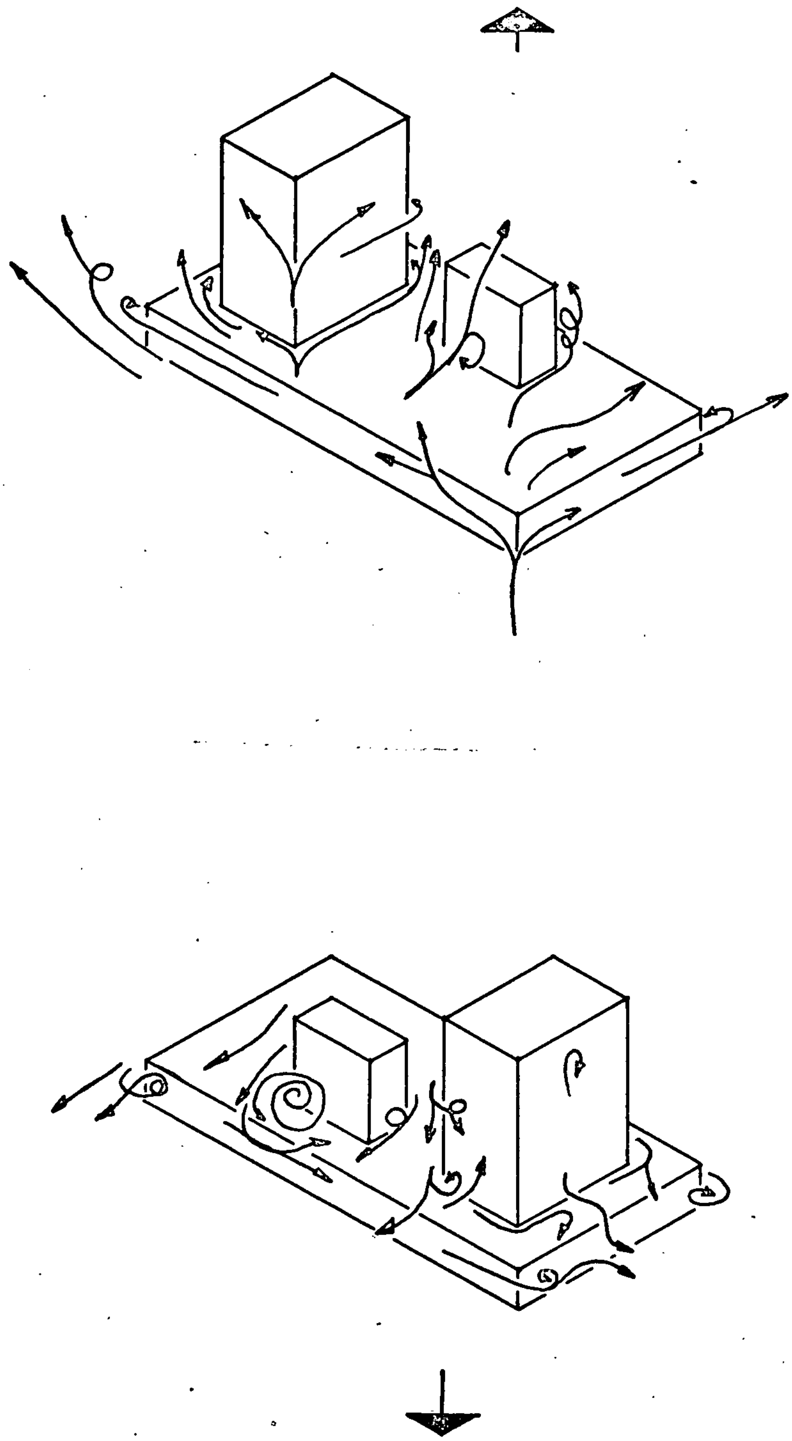


FIG 144 : GEOM II : WIND 135°

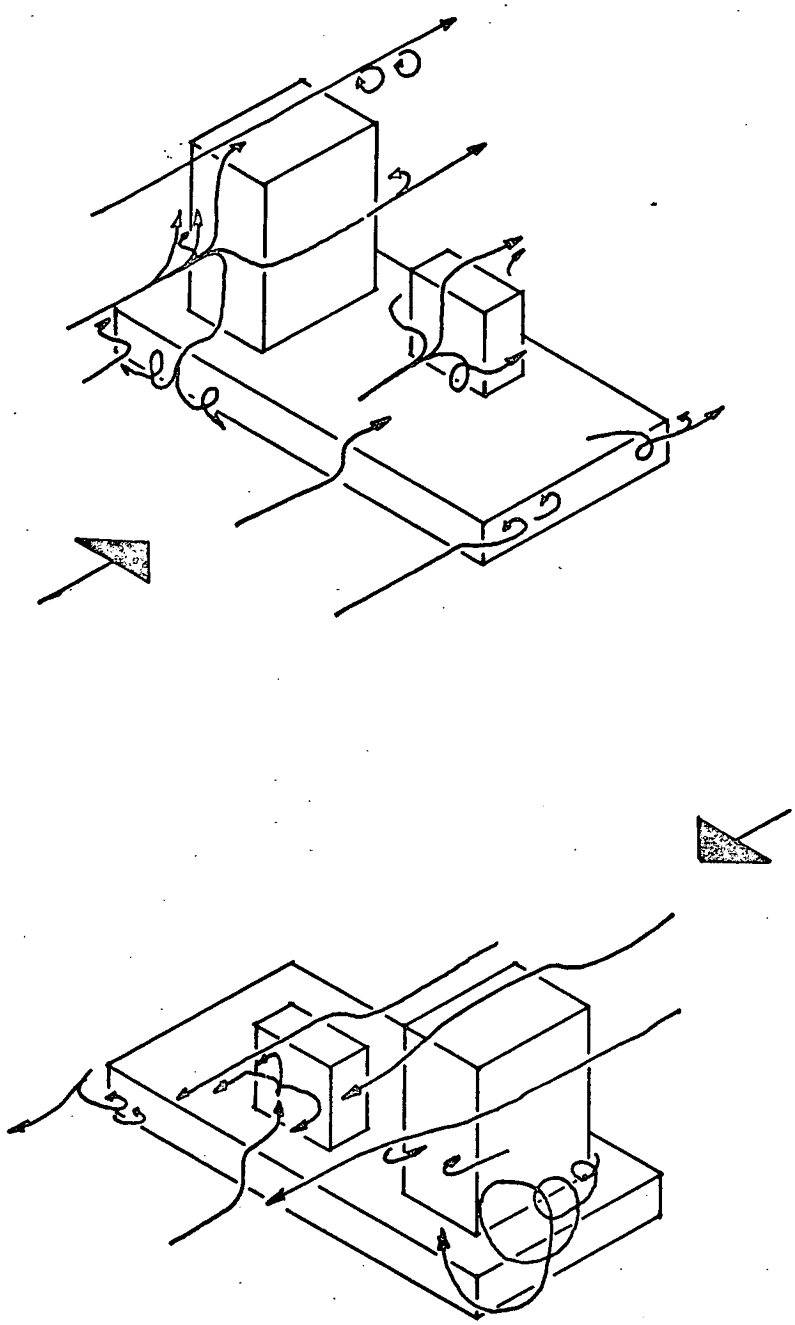


FIG 145 : GEOM II : WIND 90°

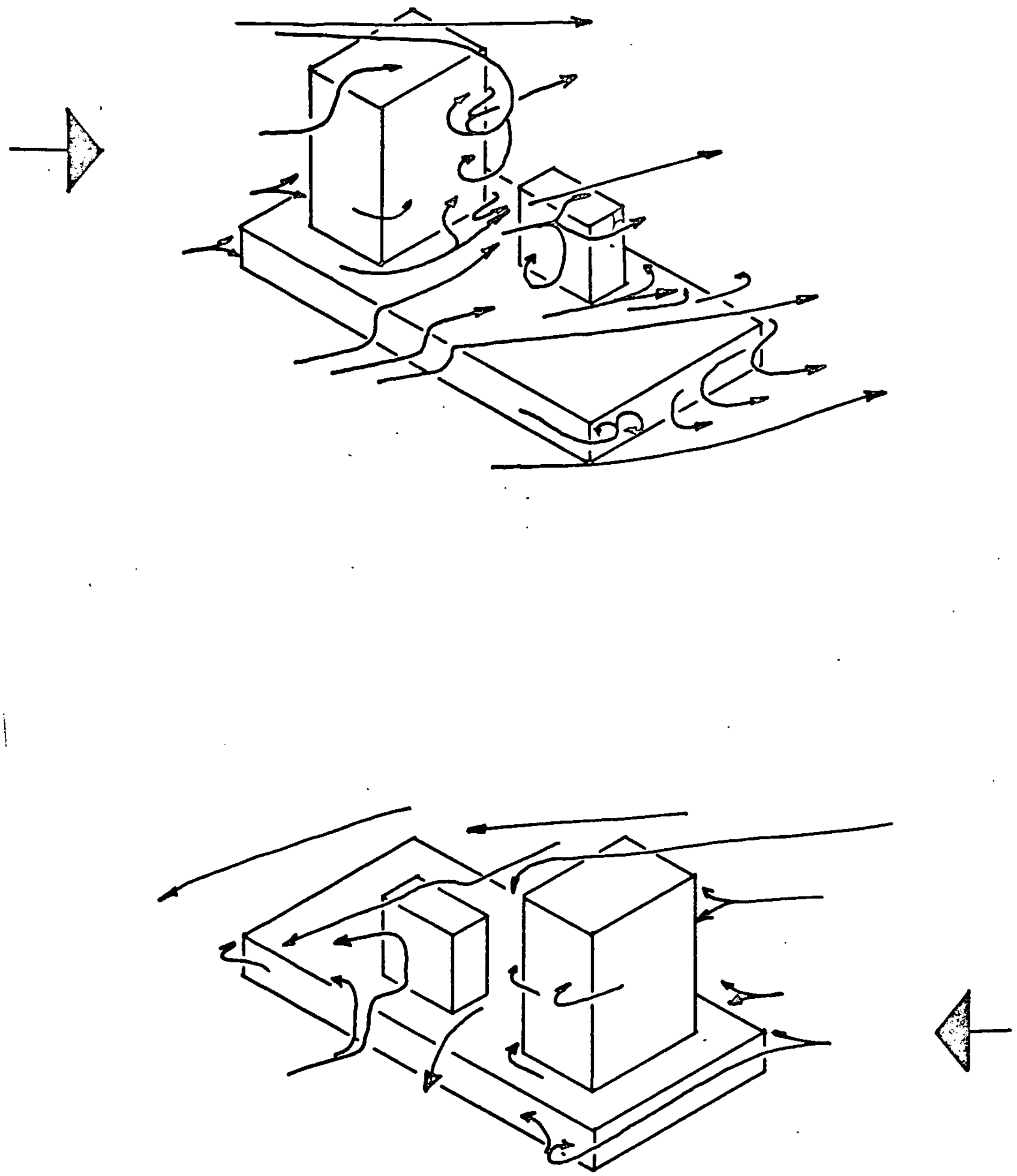


FIG 146 : GEOM II : WIND 45°

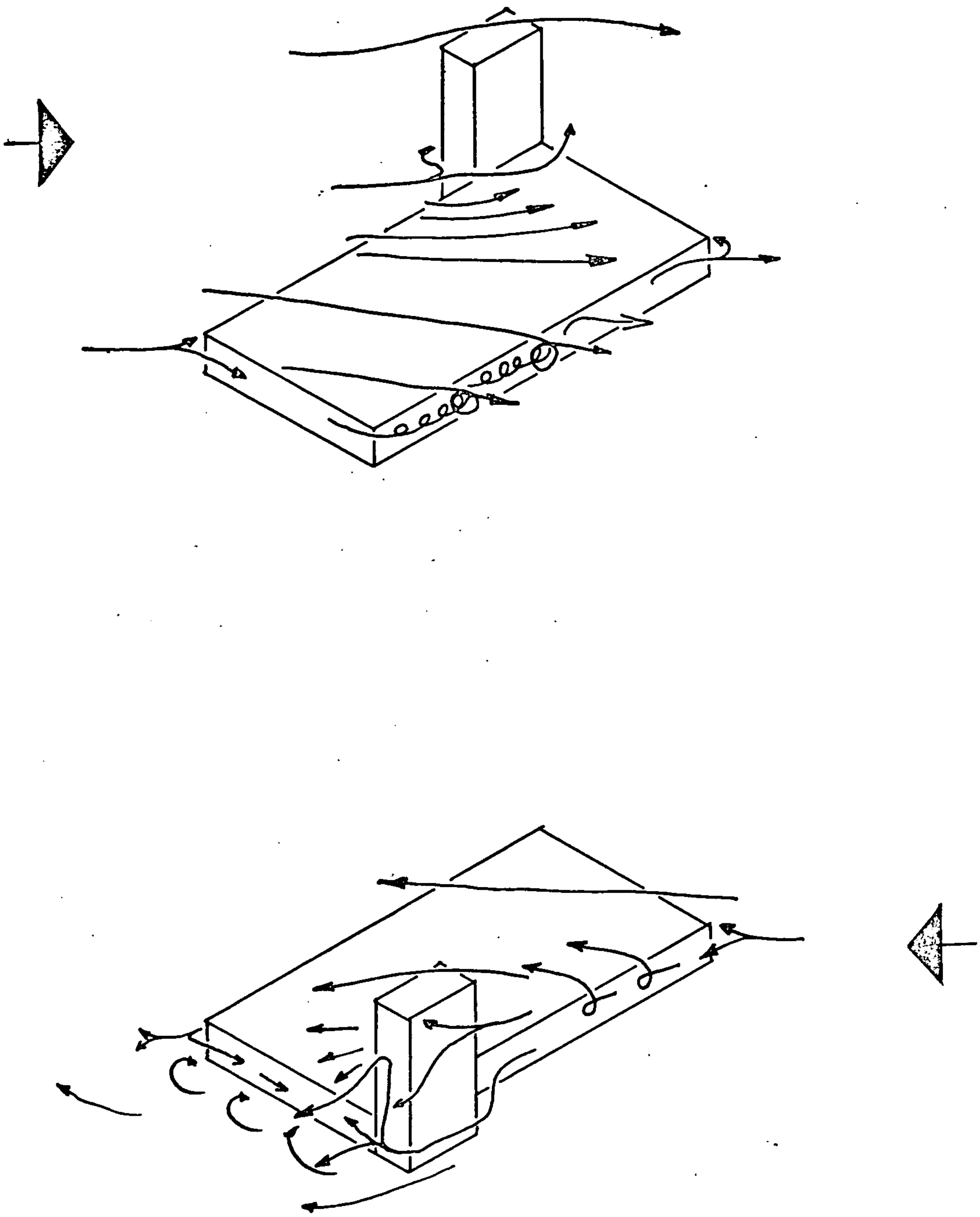


FIG 147 : GEOM 12 : WIND 315°

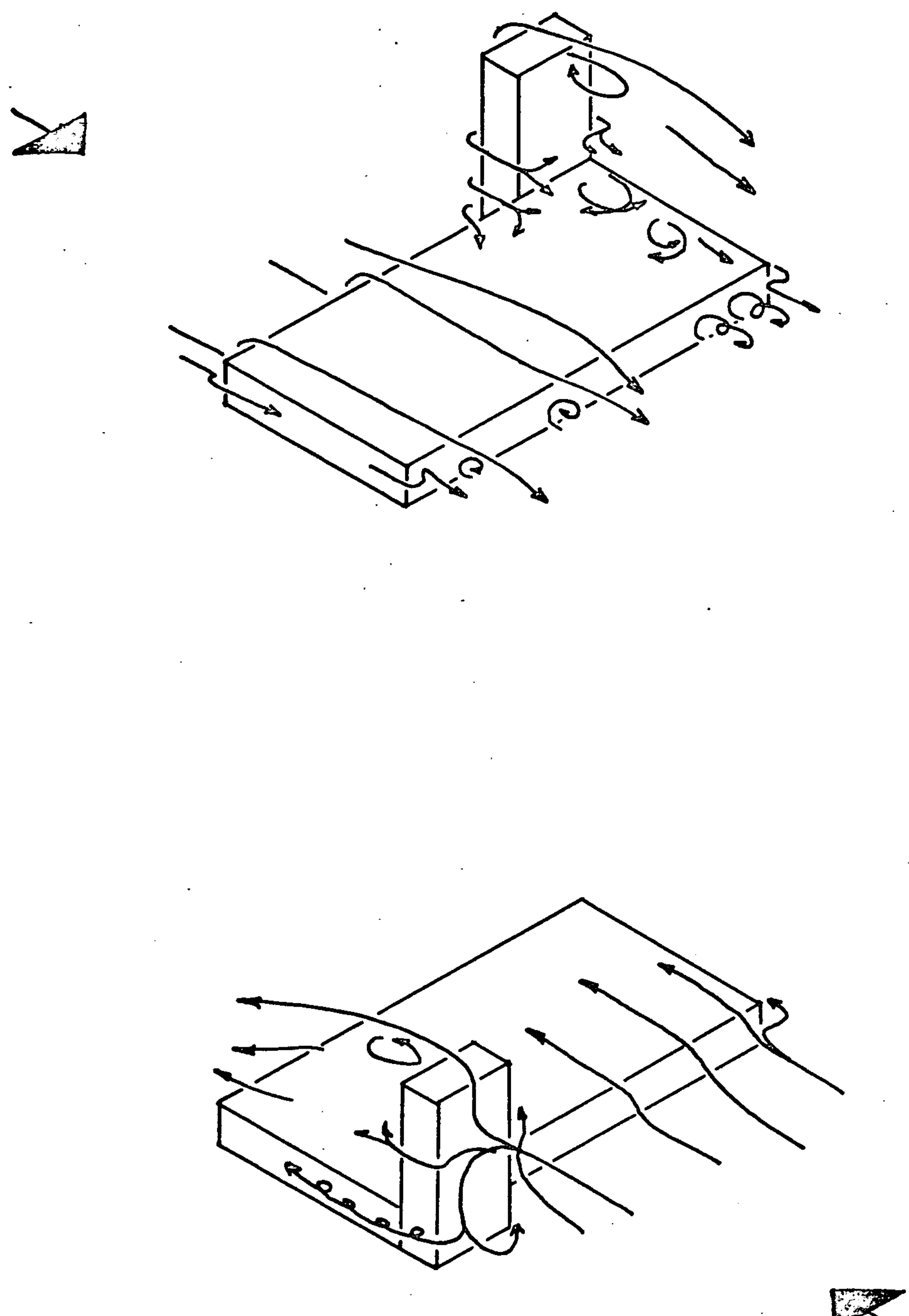


FIG 148 : GEOM 12 : WIND 270°

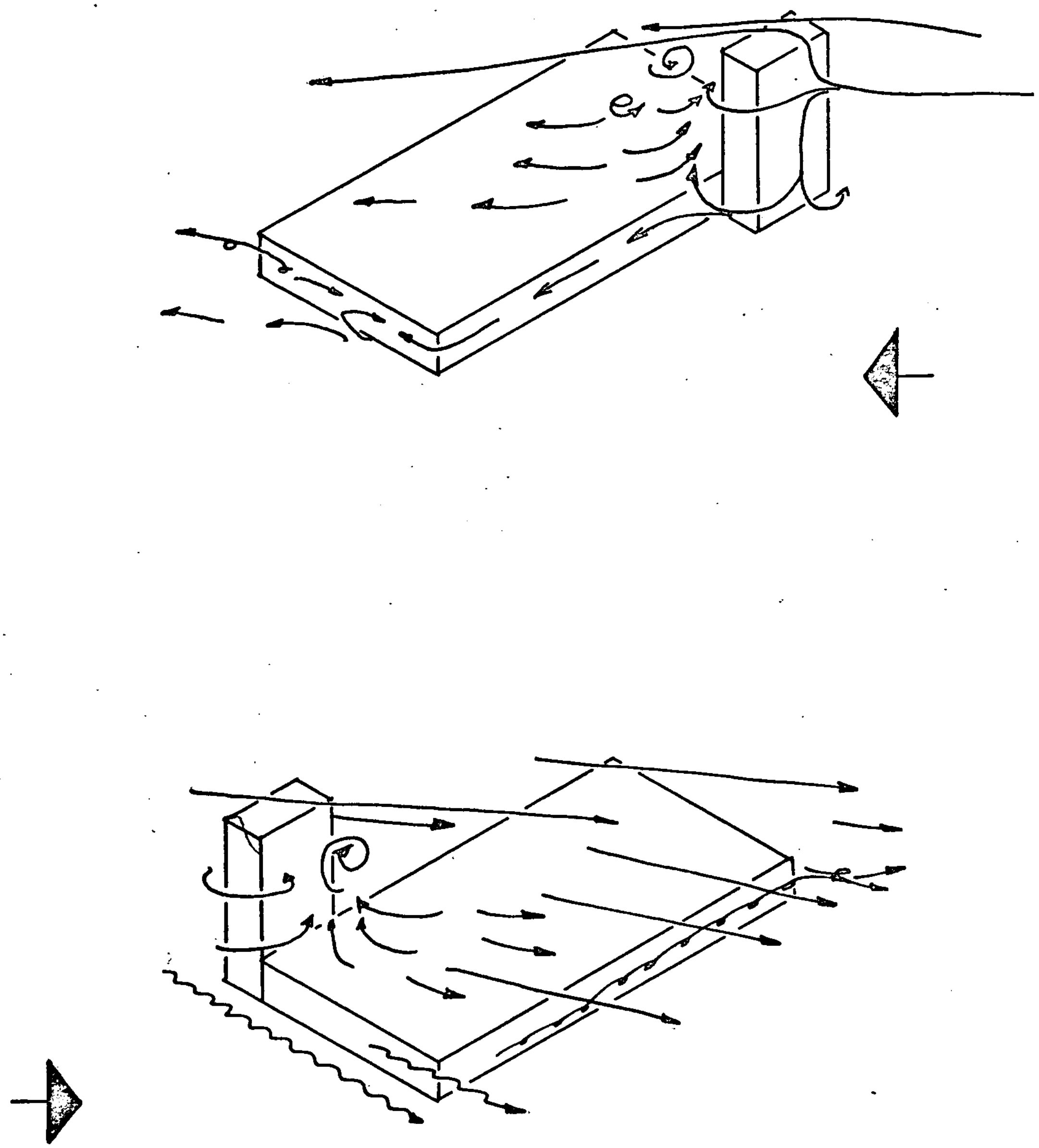
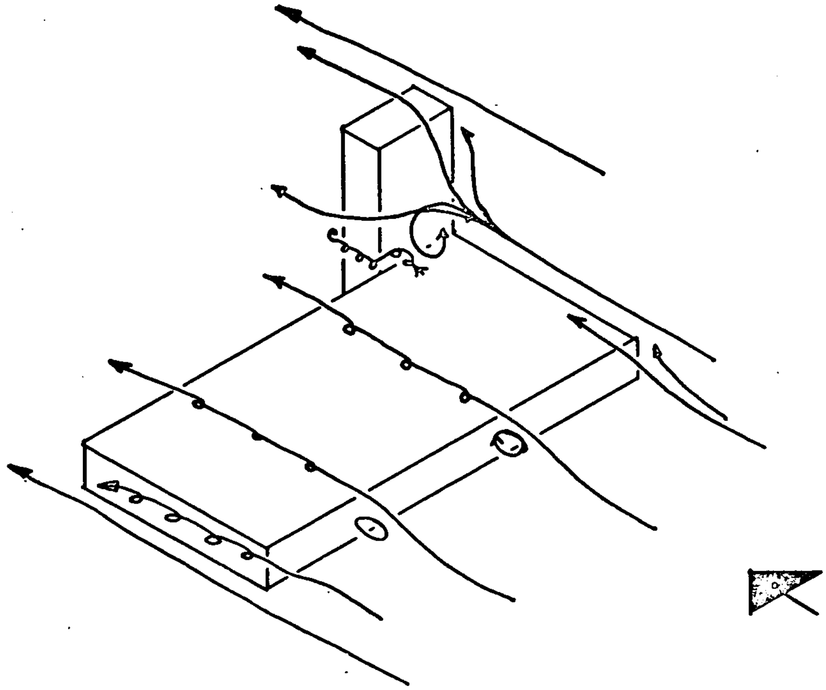


FIG 149 : GEOM 12 : WIND 225°



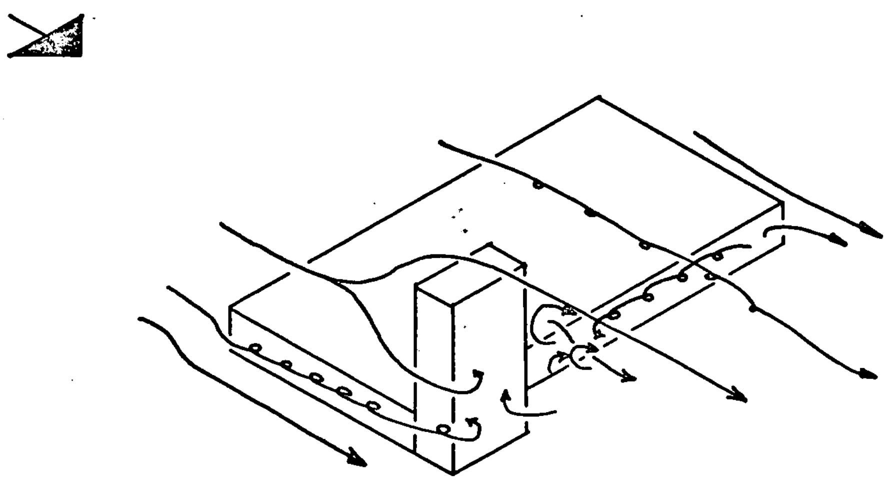


FIG 150 : GEOM 12 : WIND 90°

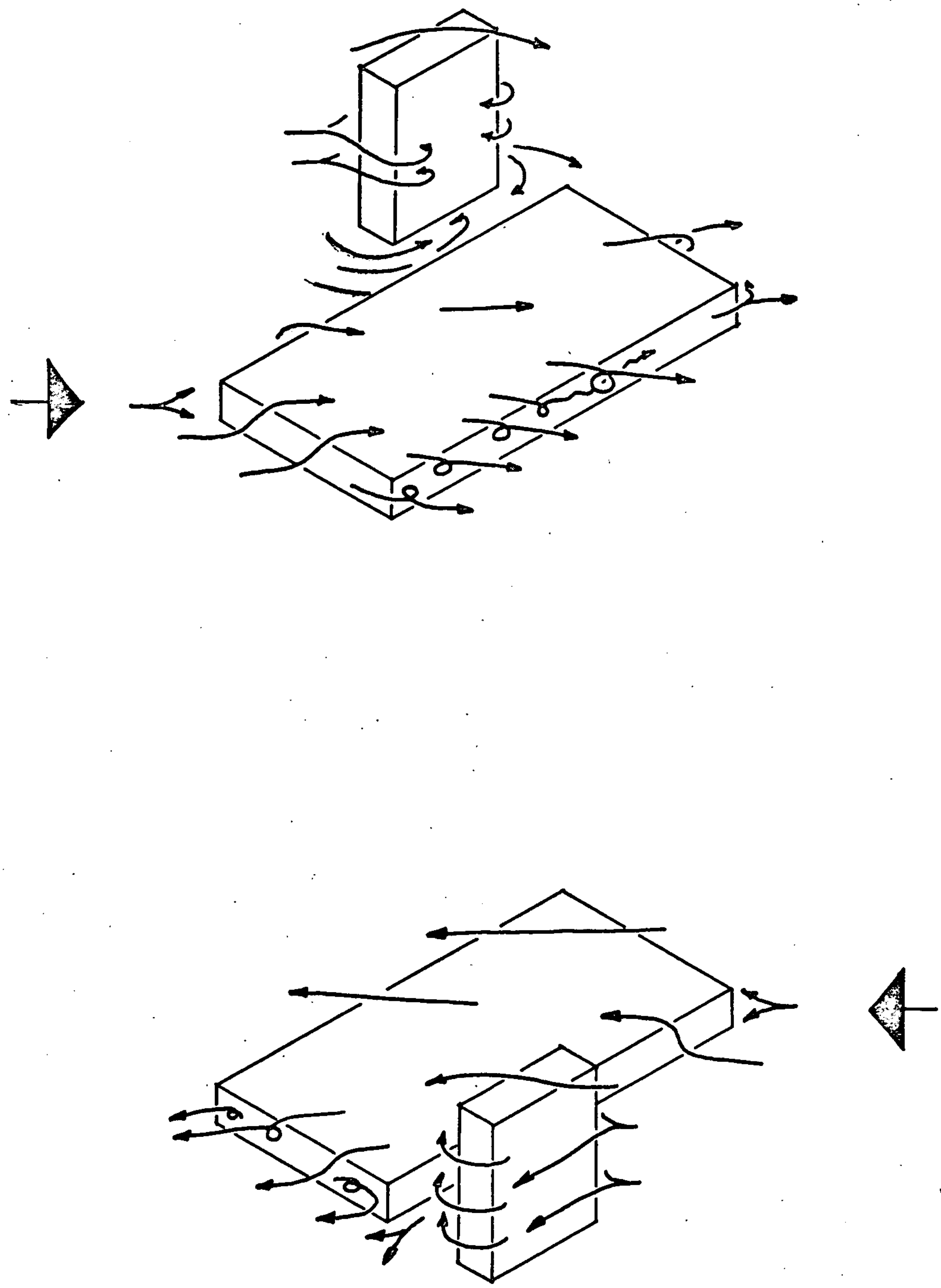


FIG 151 : GEOM 13 : WIND 315°

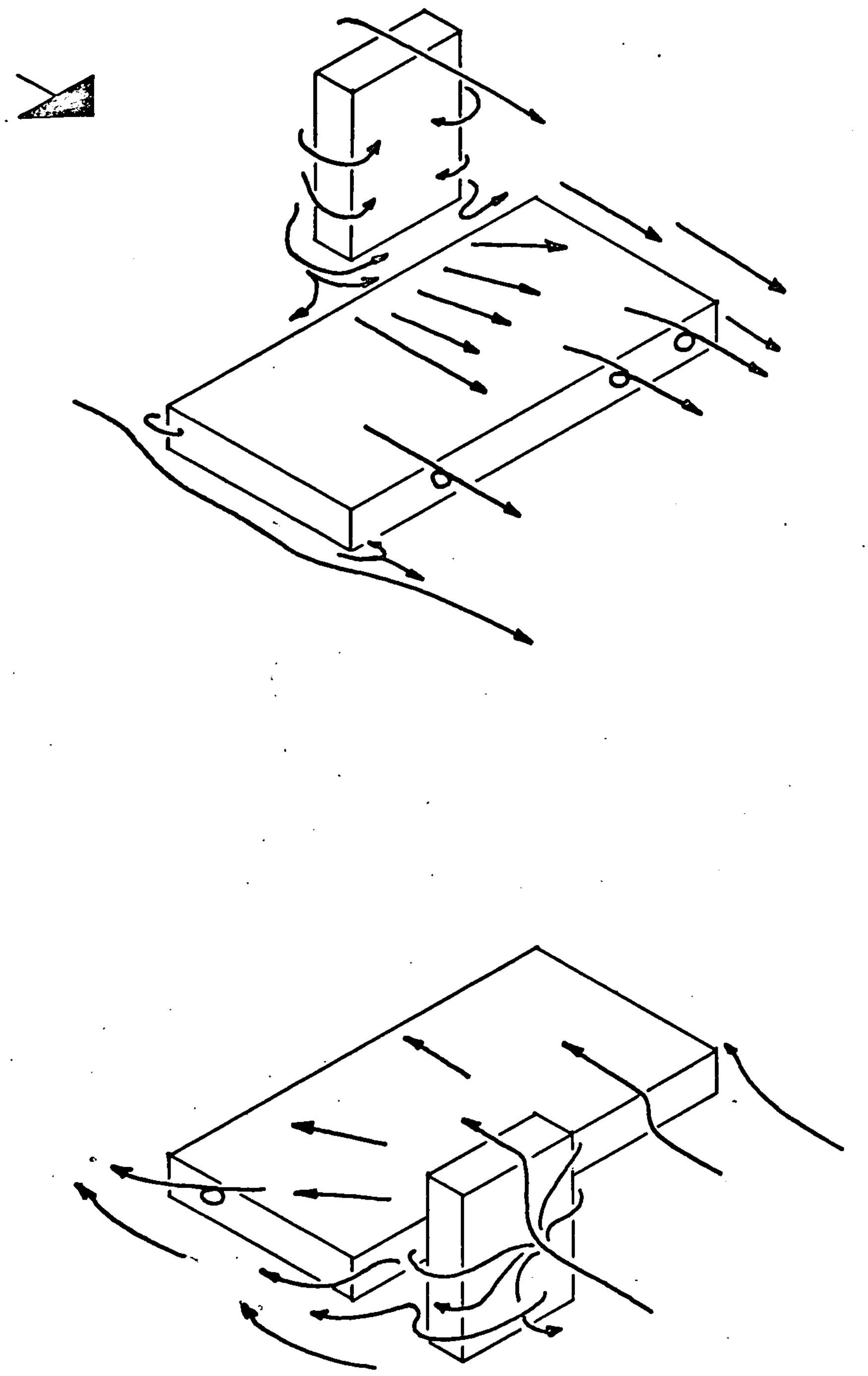
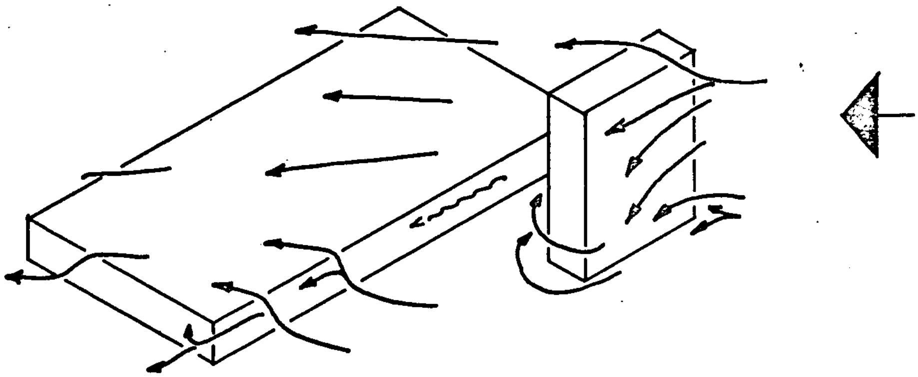


FIG 152: GEOM 13 : WIND 270°



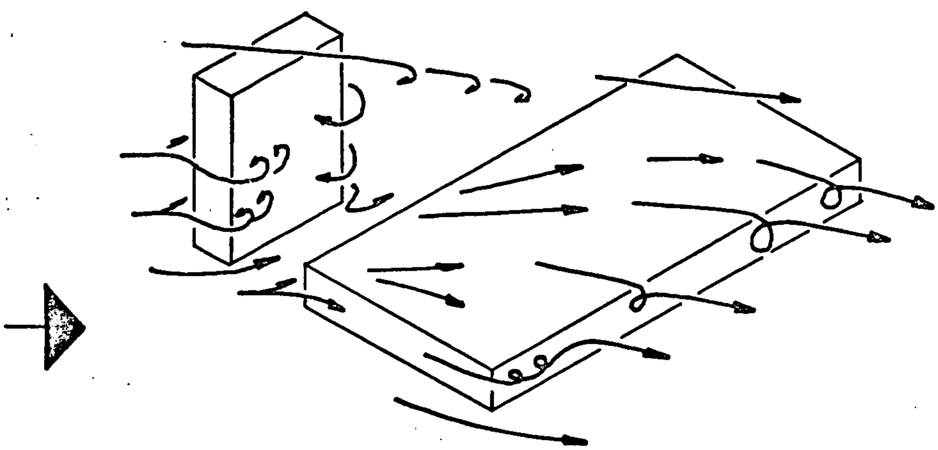


FIG 153 : GEOM 13 : WIND 225°

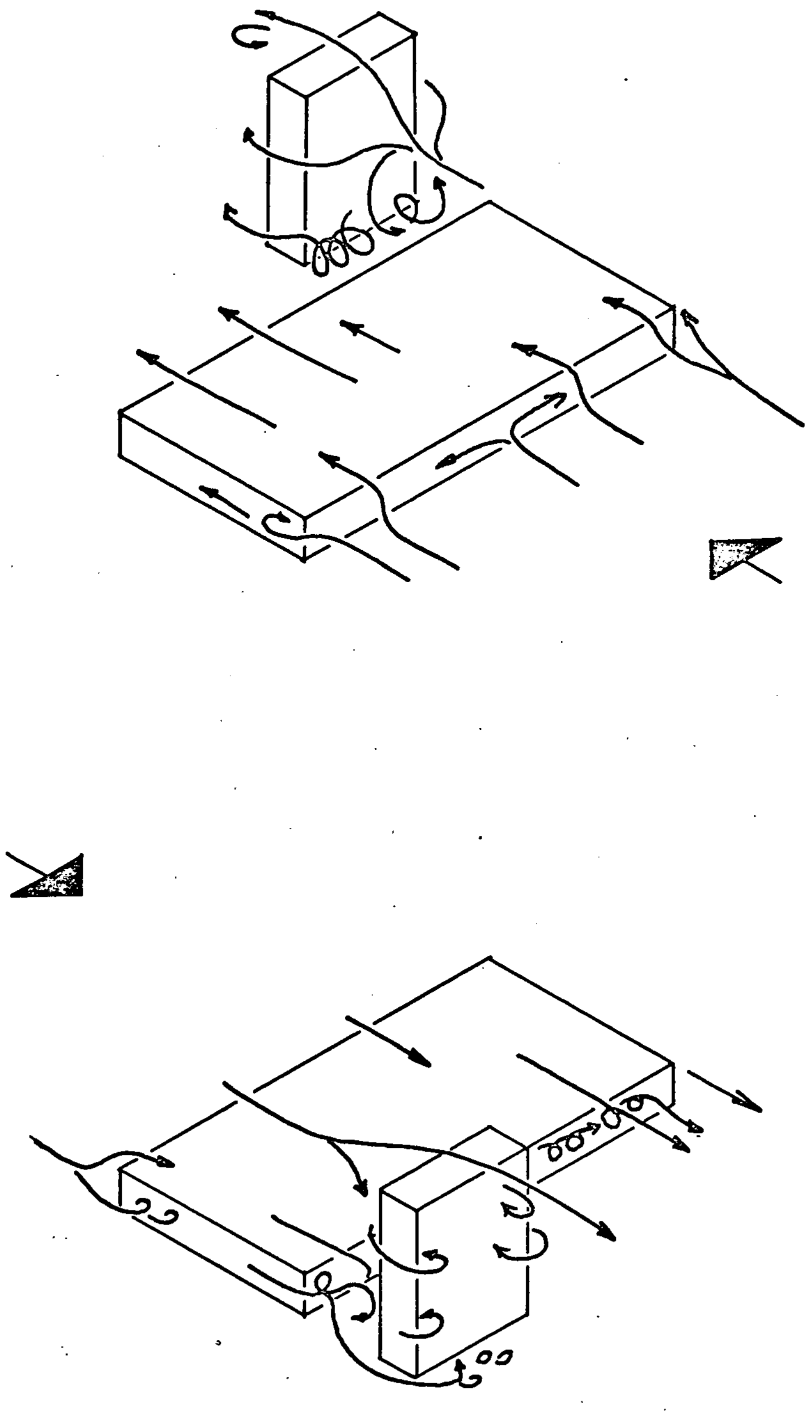


FIG 154 : GEOM 13 : WIND 90°

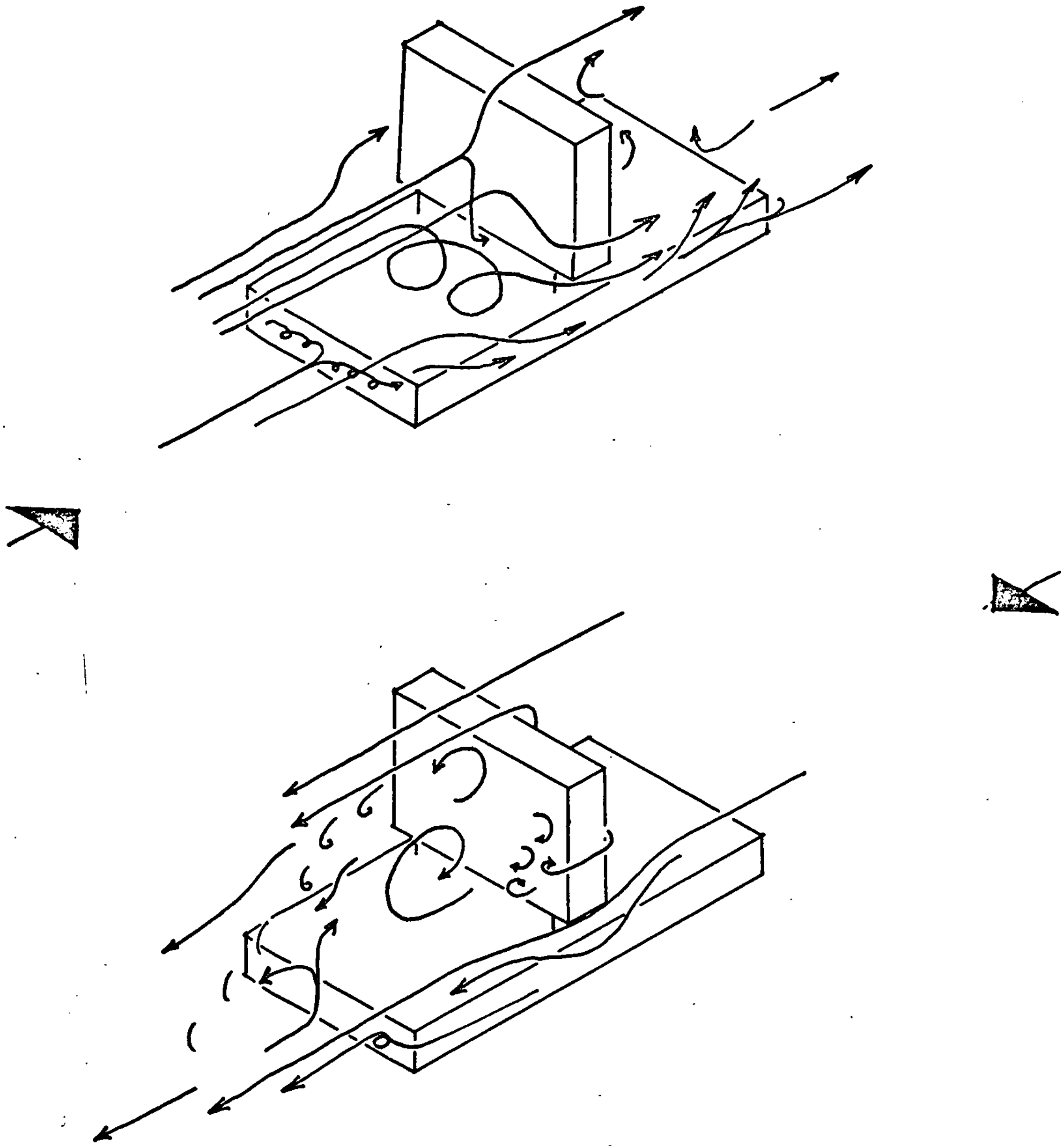


FIG 155 : GEOM 14 : WIND 0°

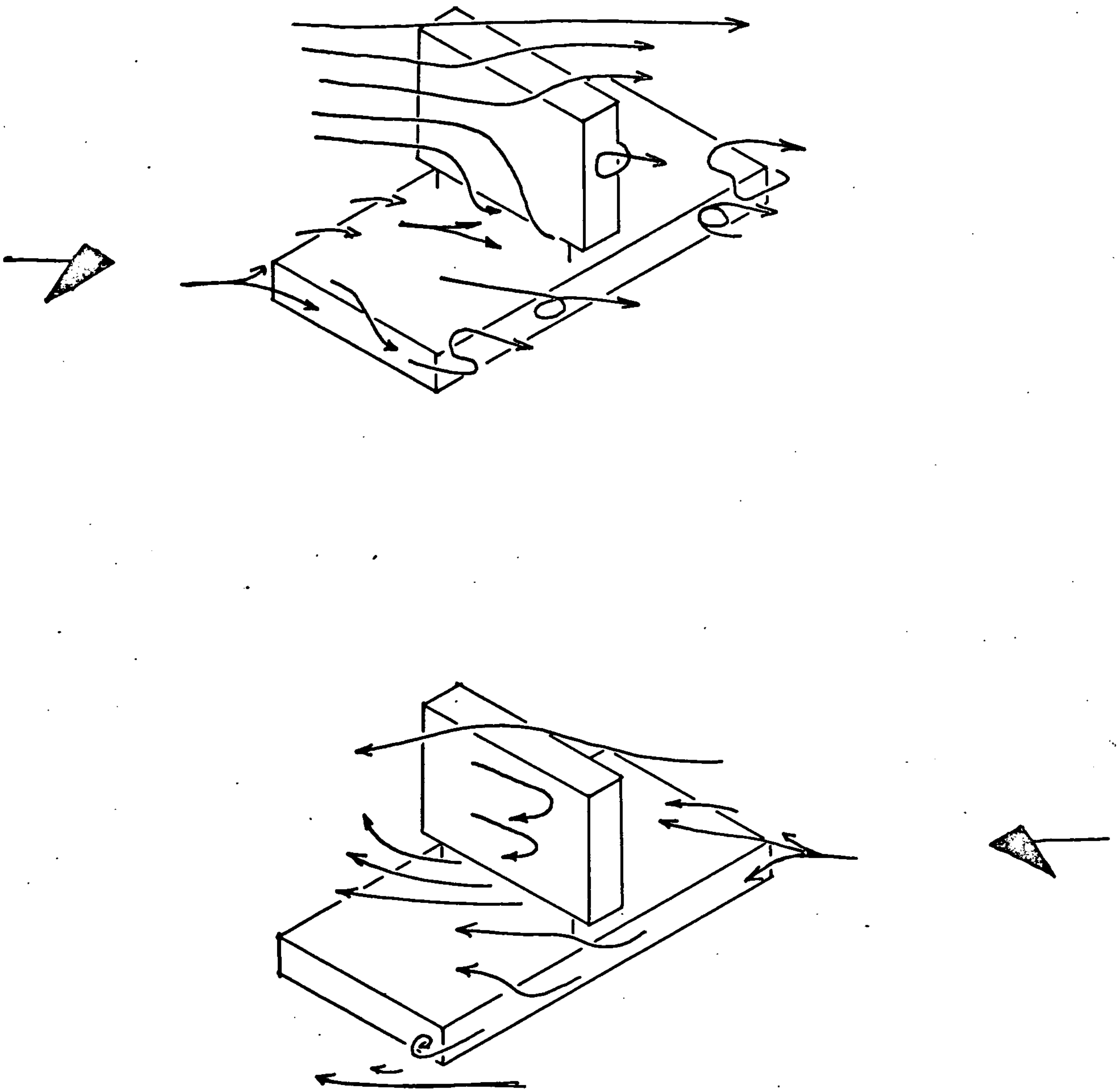


FIG 156 : GEOM 14 : WIND 315°

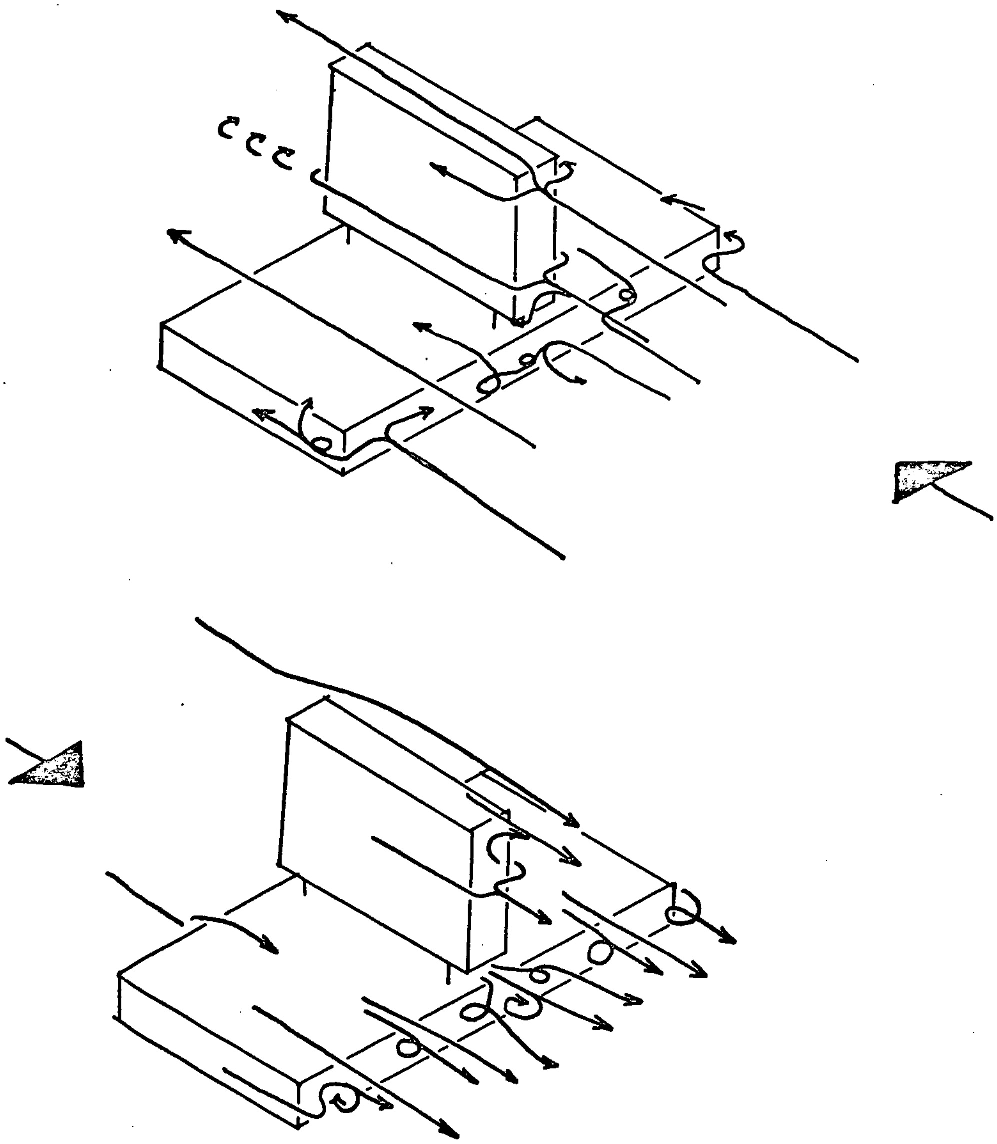


FIG 157 : GEOM 14 : WIND 270°

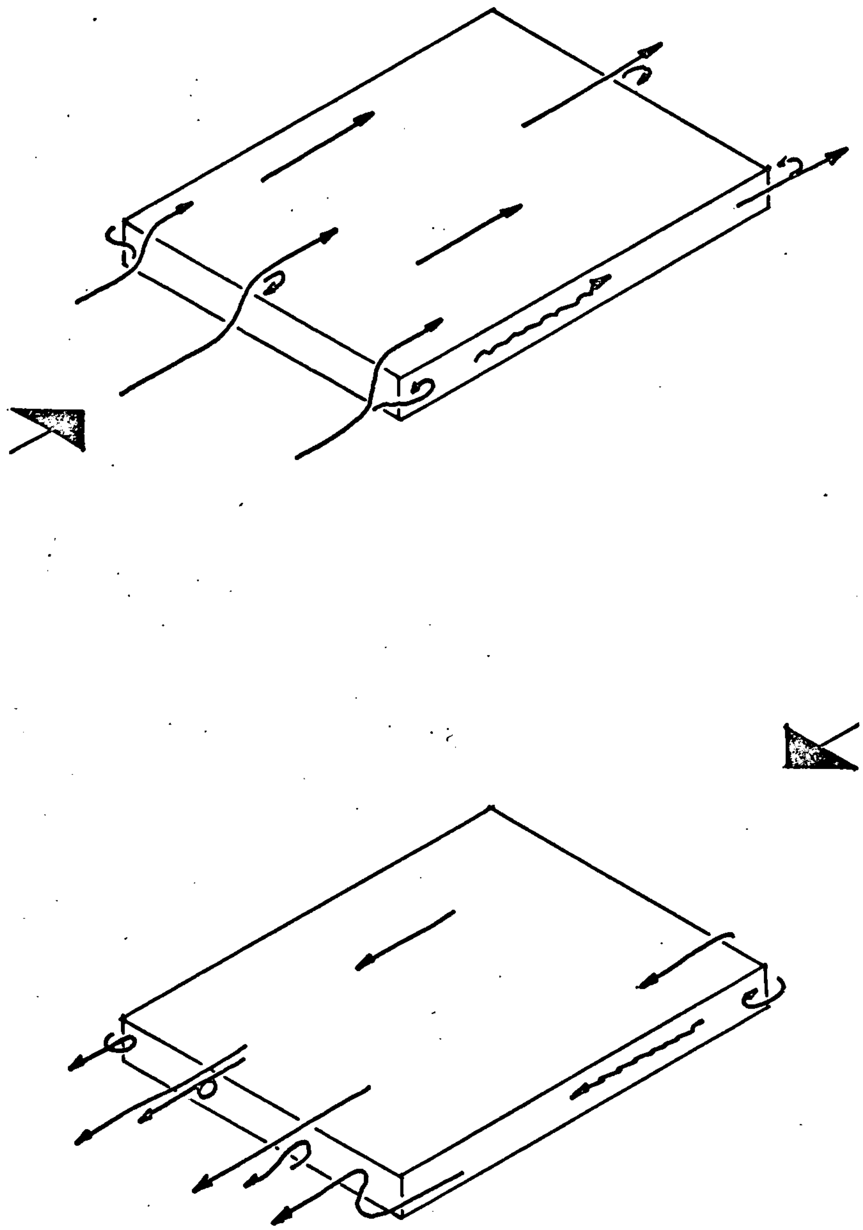


FIG 158 : GEOM 15 : WIND 0°

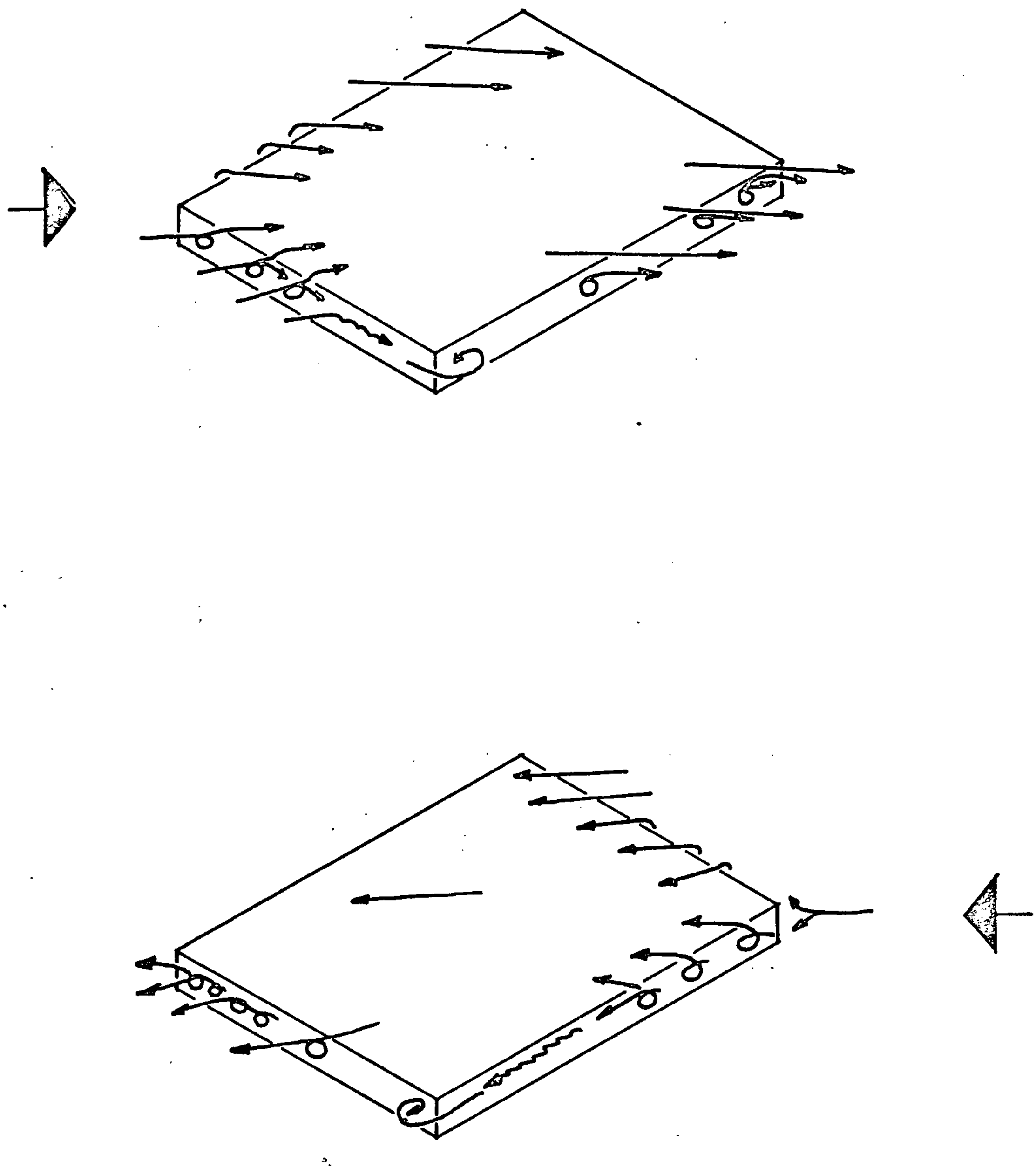


FIG 159 : GEOM 15 : WIND 315°

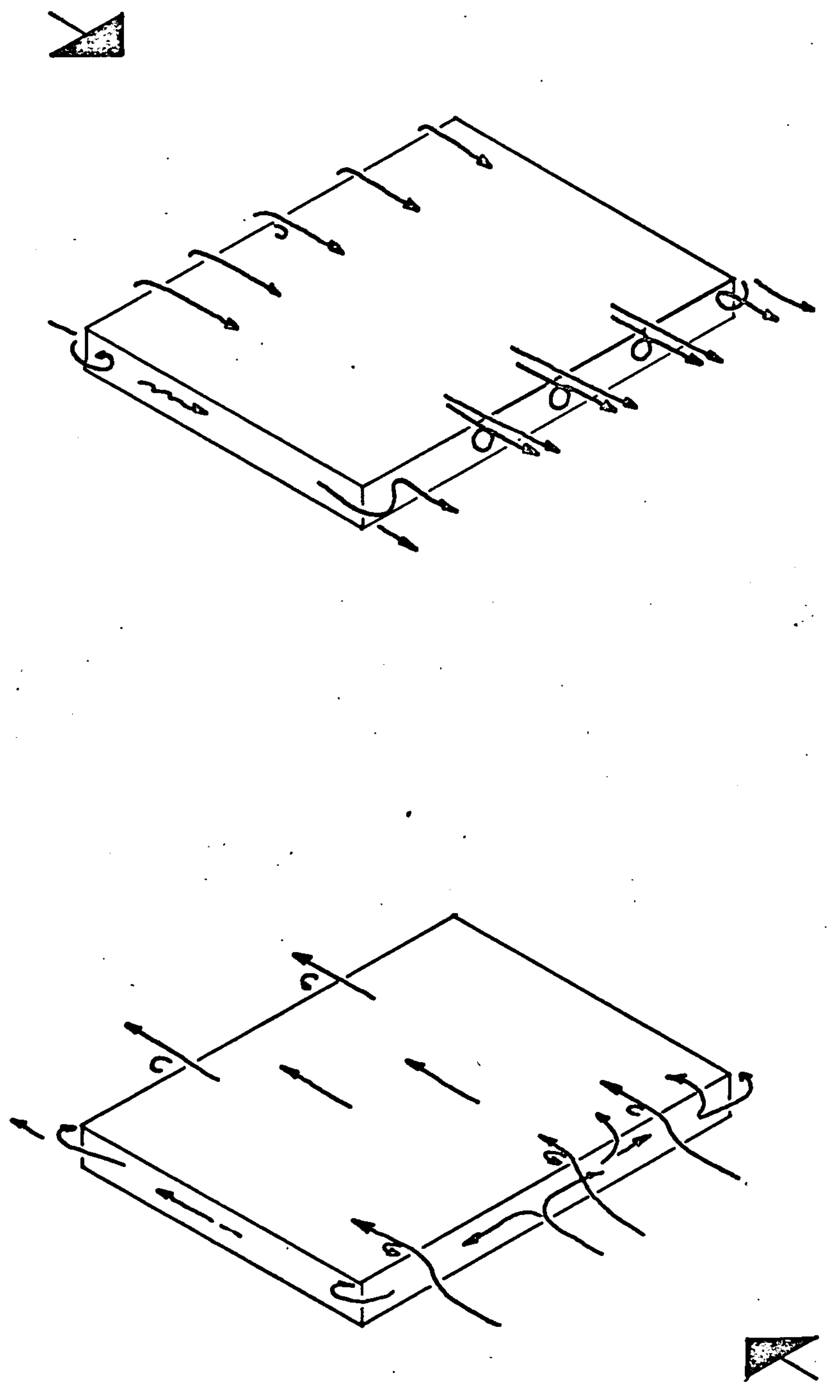


FIG 160 : GEOM 15 : WIND 270°

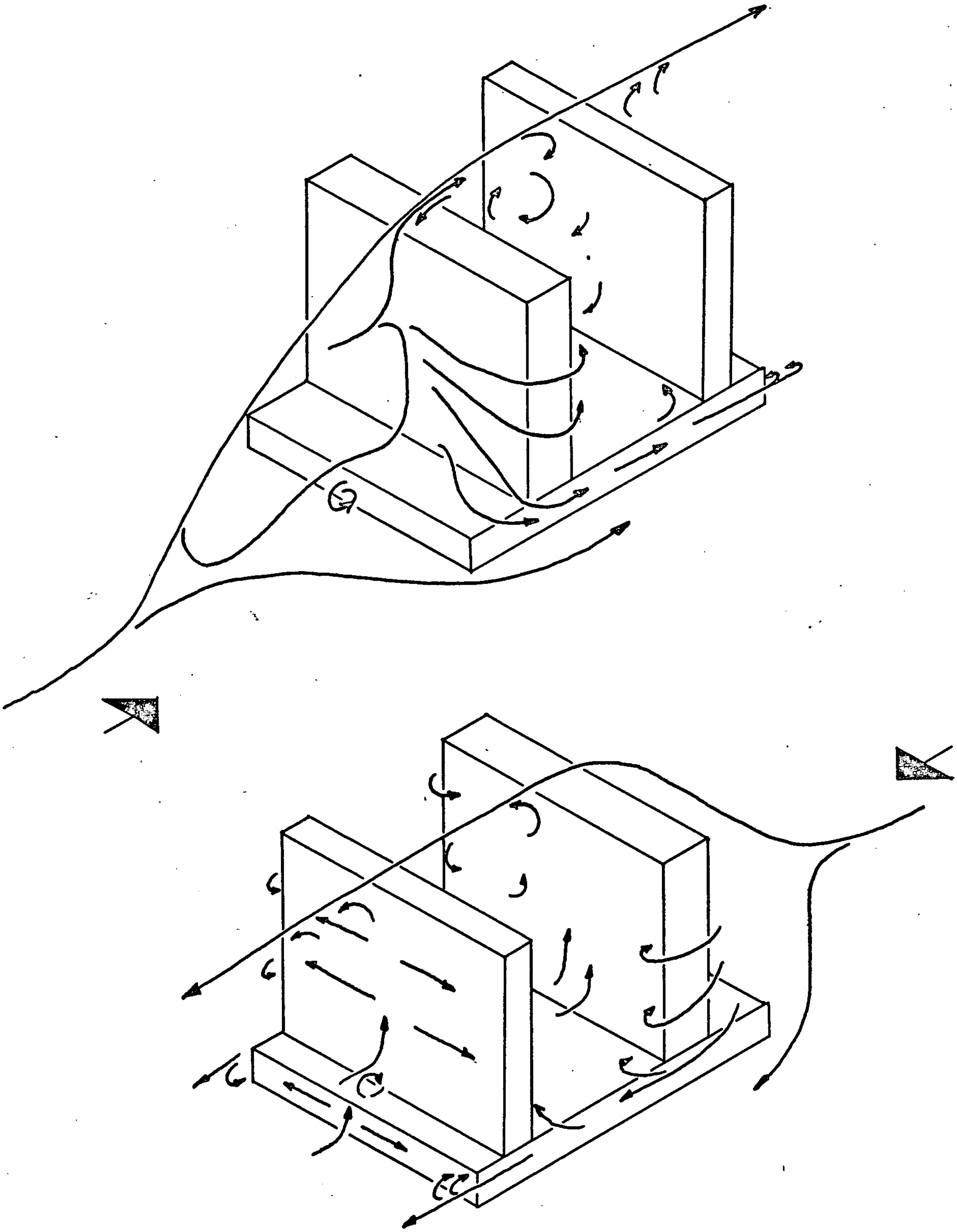


FIG 161 : GEOM 16 : WIND 0°

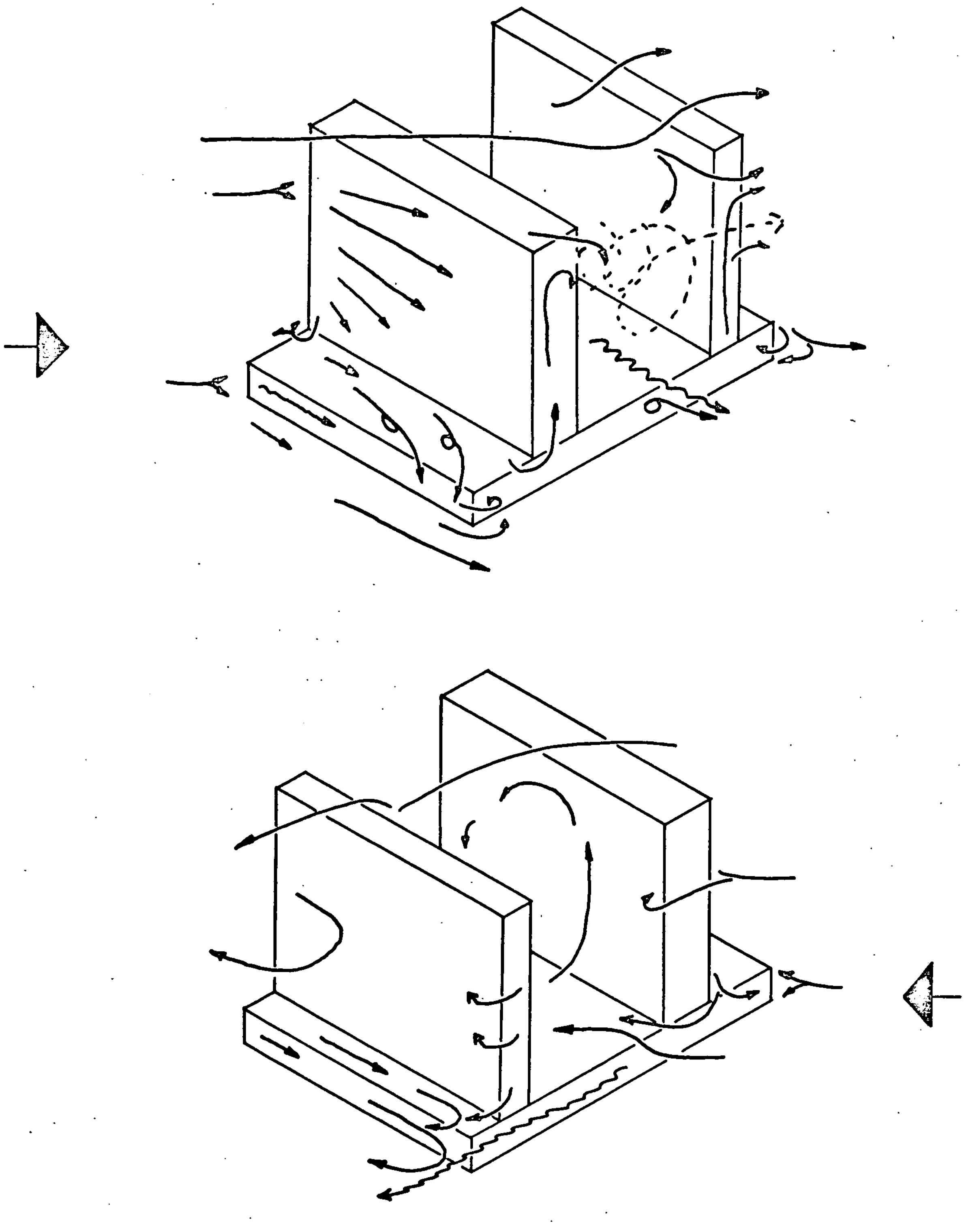


FIG 162 : GEOM 16 : WIND 315°

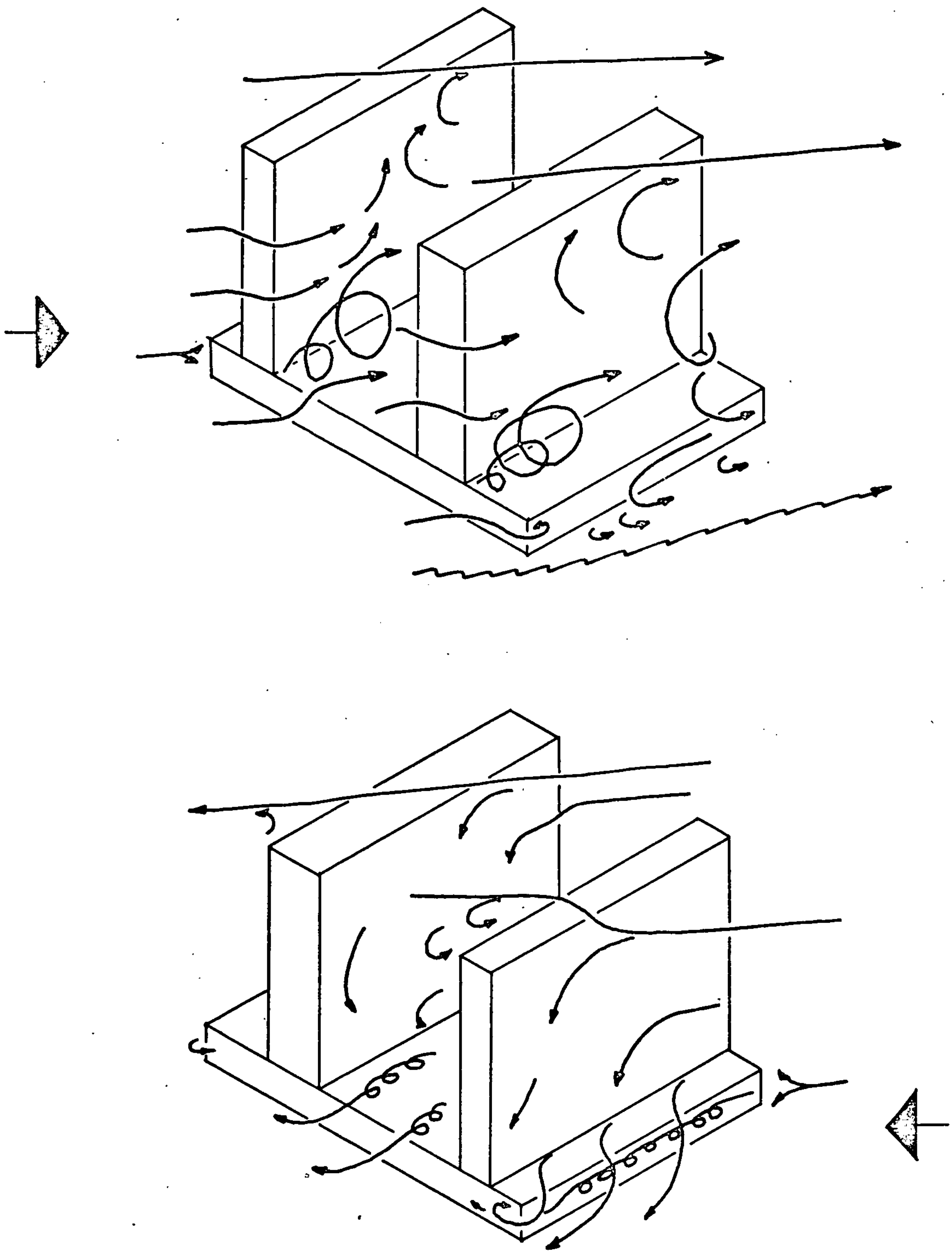


FIG 163 : GEOM 16 : WIND 225°

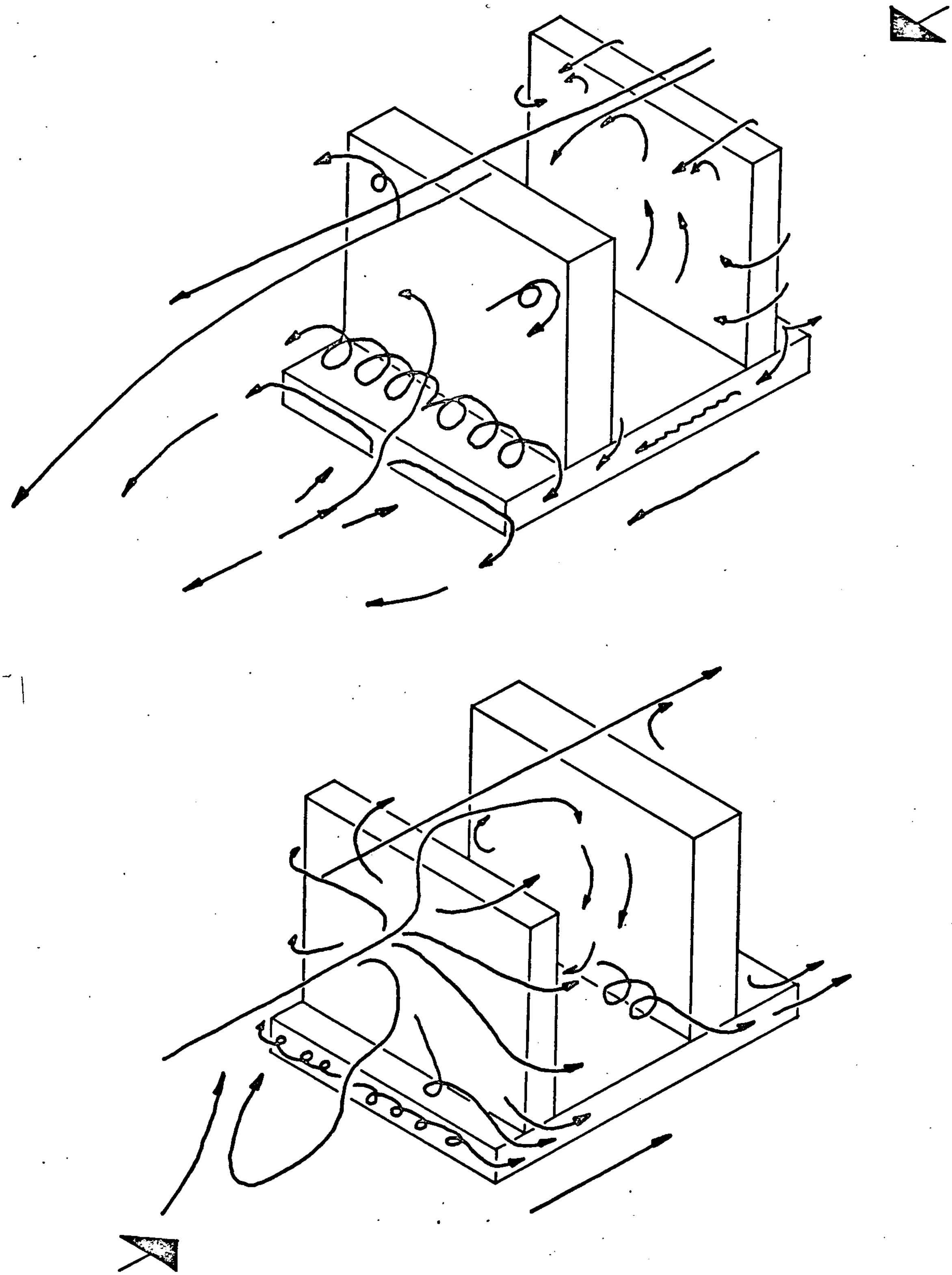


FIG 164 : GEOM 16 : WIND 180°

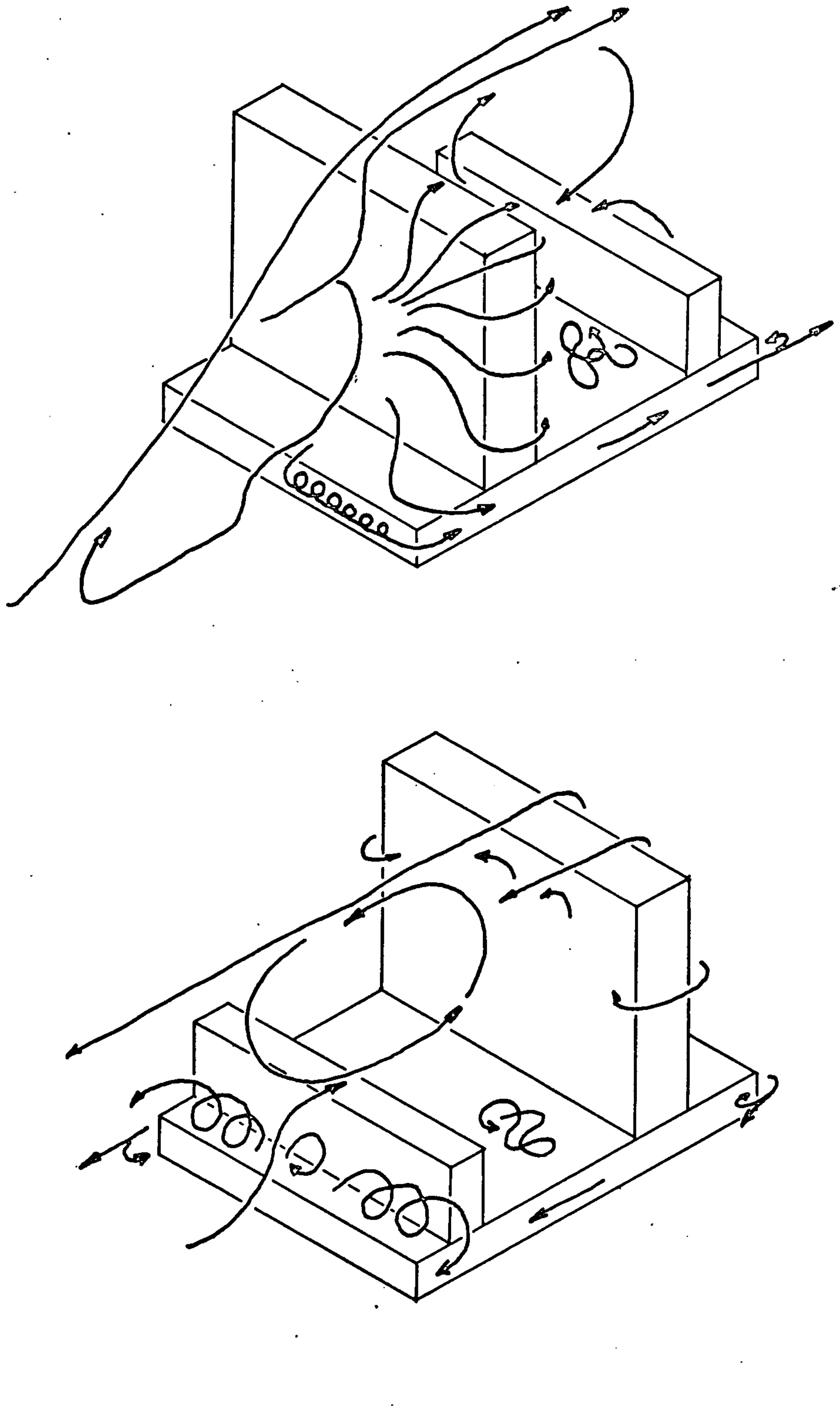


FIG 165 : GEOM 17 : WIND O°

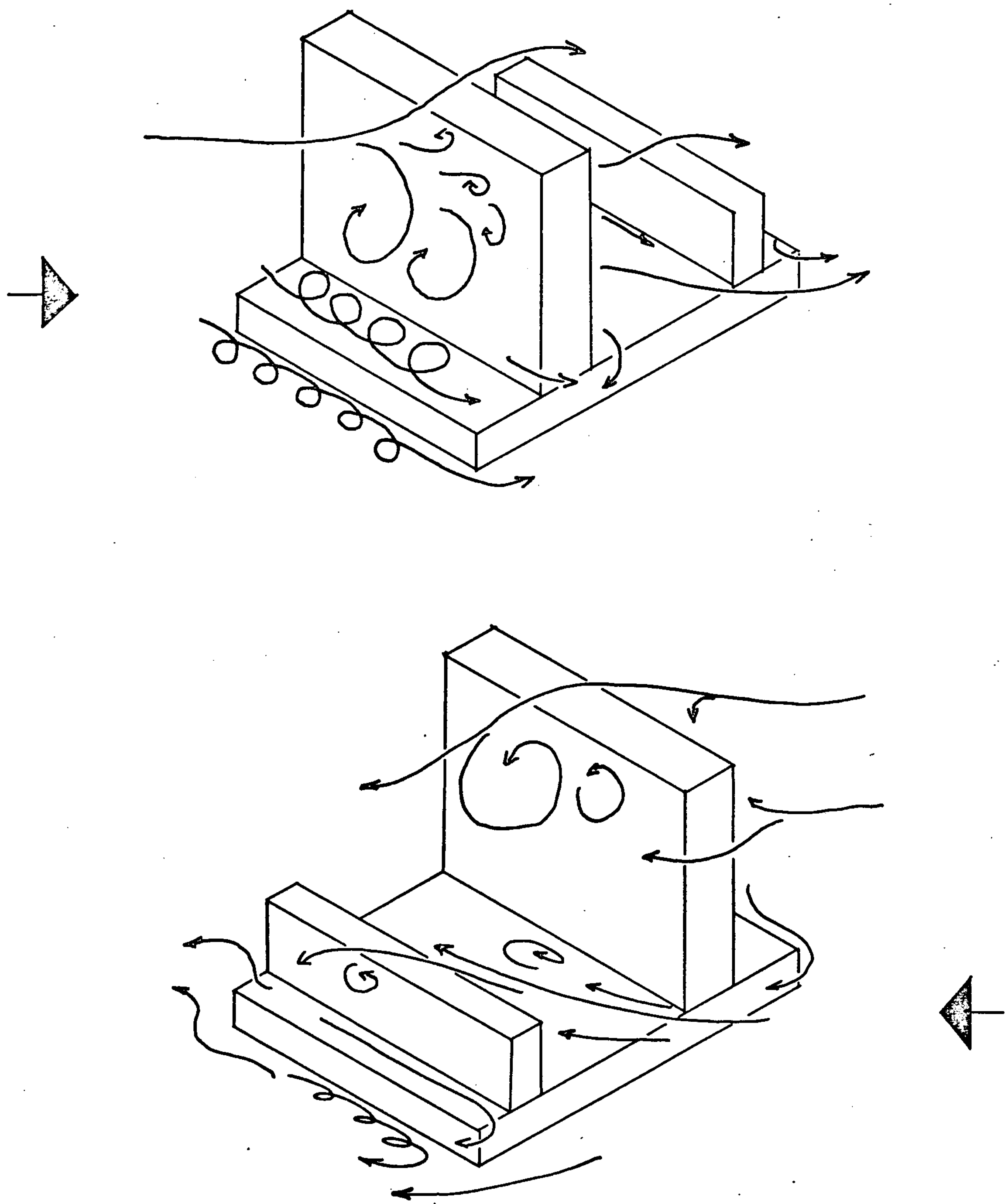


FIG 166 : GEOM 17 : WIND 315°

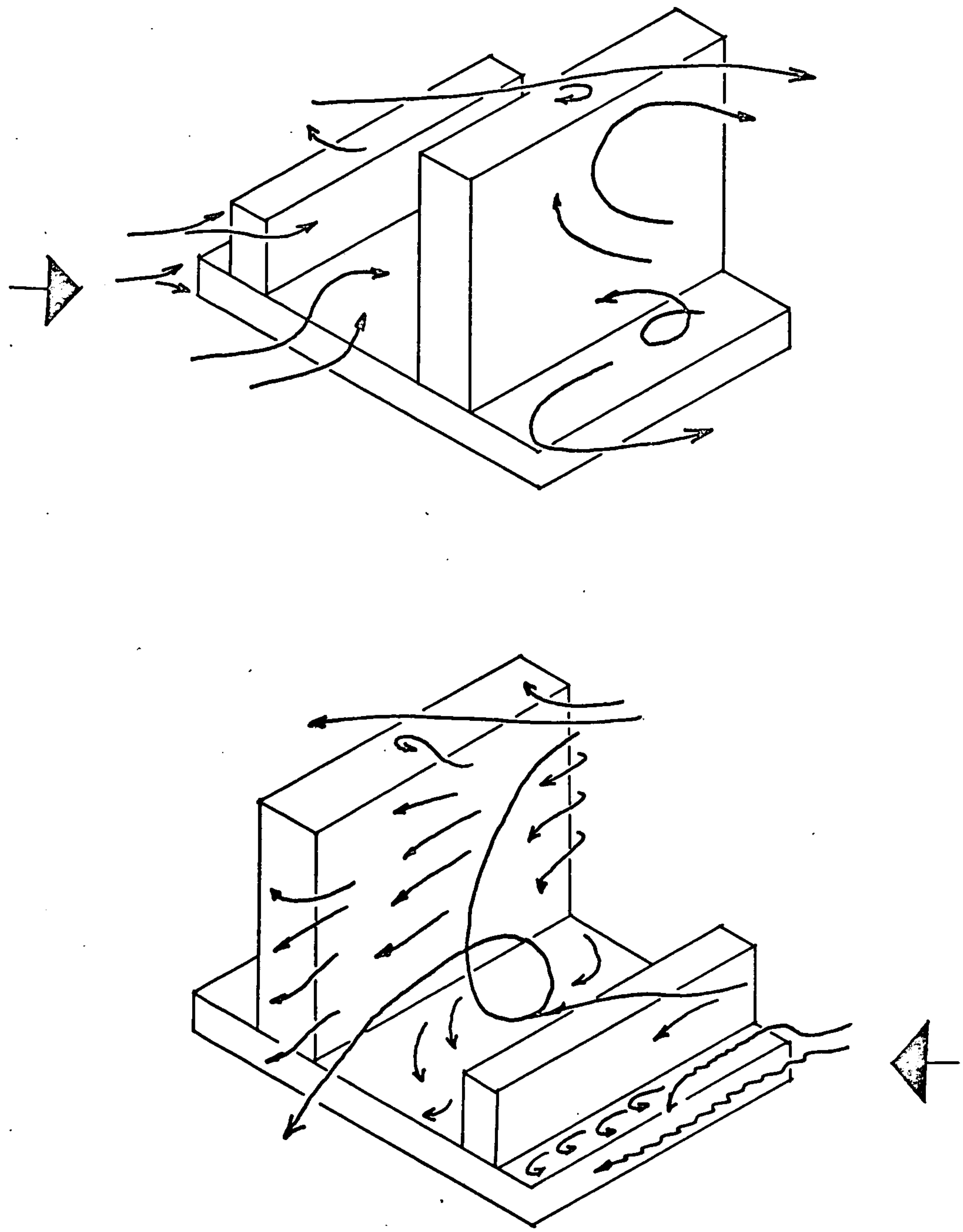


FIG 167 : GEOM 17 : WIND 225°

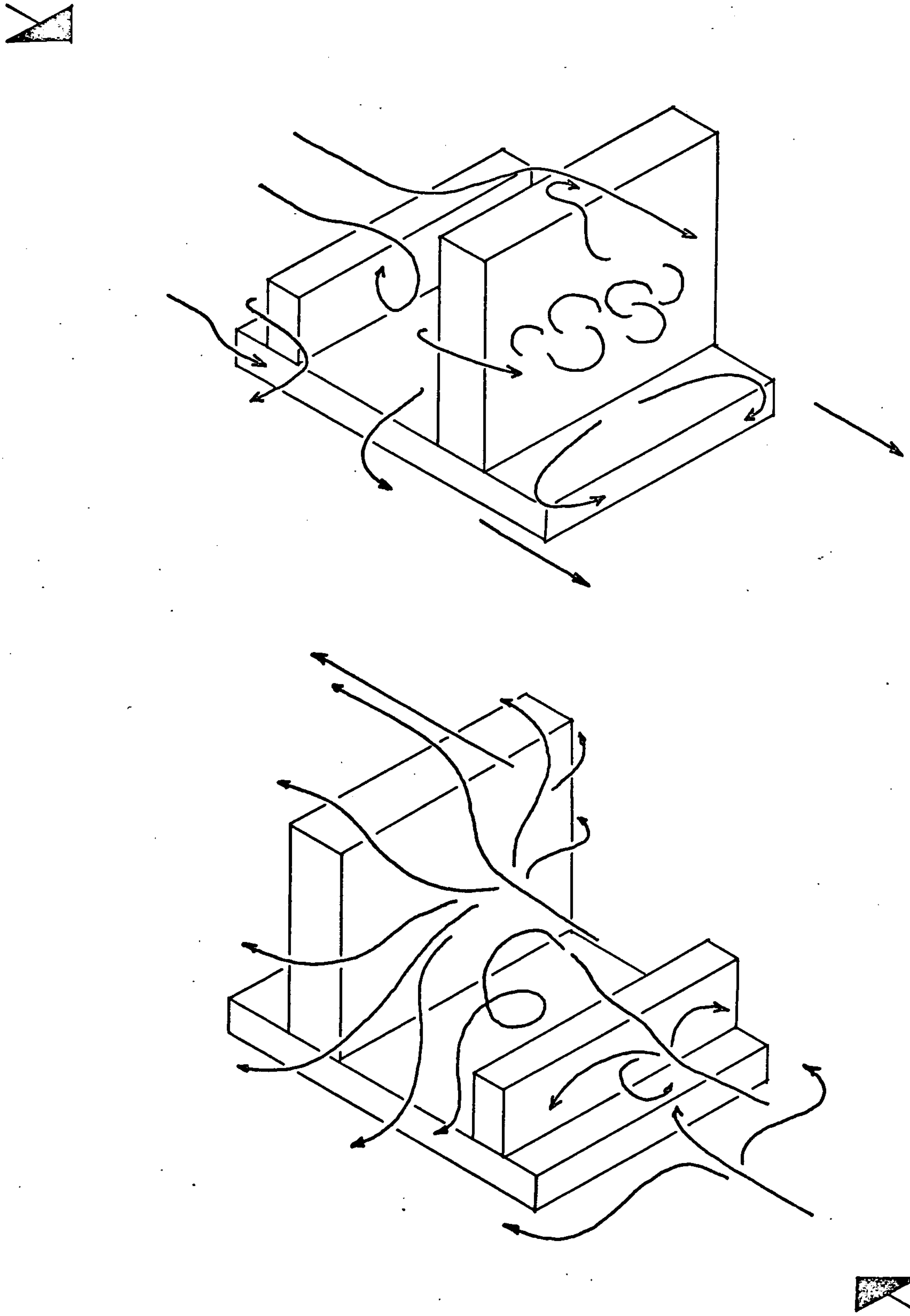


FIG 168 : GEOM 17 : WIND 180°

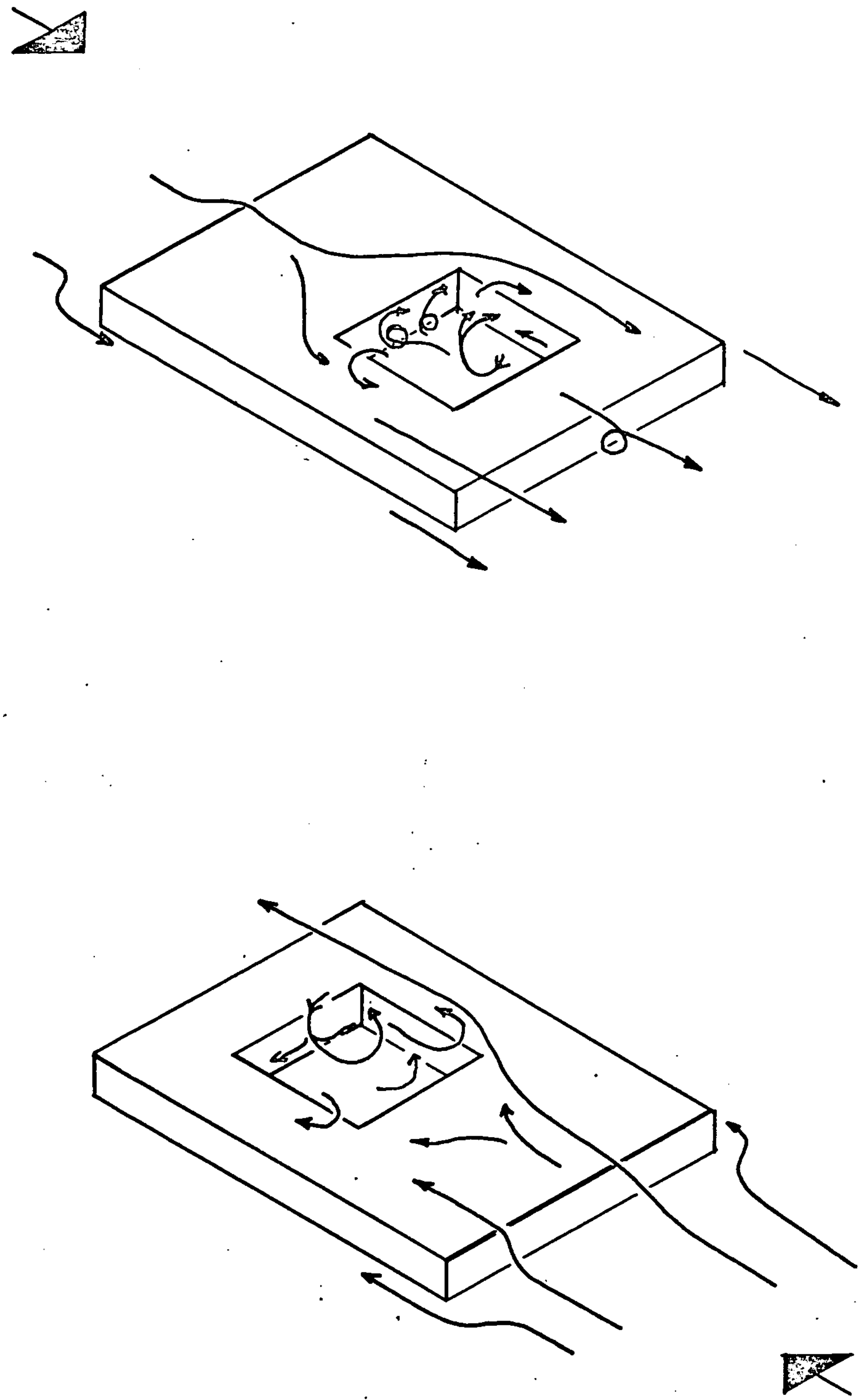


FIG 169 : GEOM 18 : WIND 0°

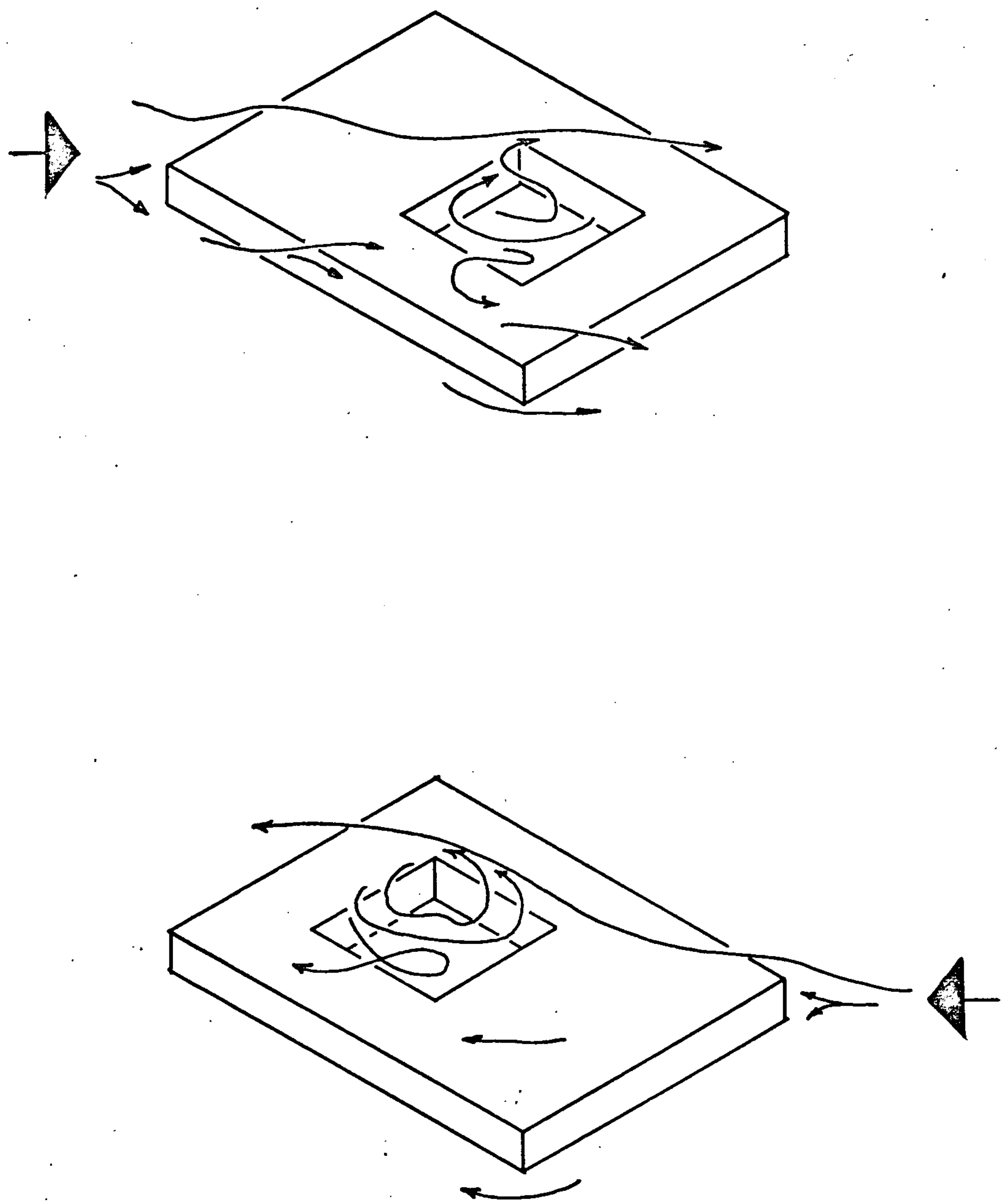


FIG 170 : GEOM 18 : WIND 315°

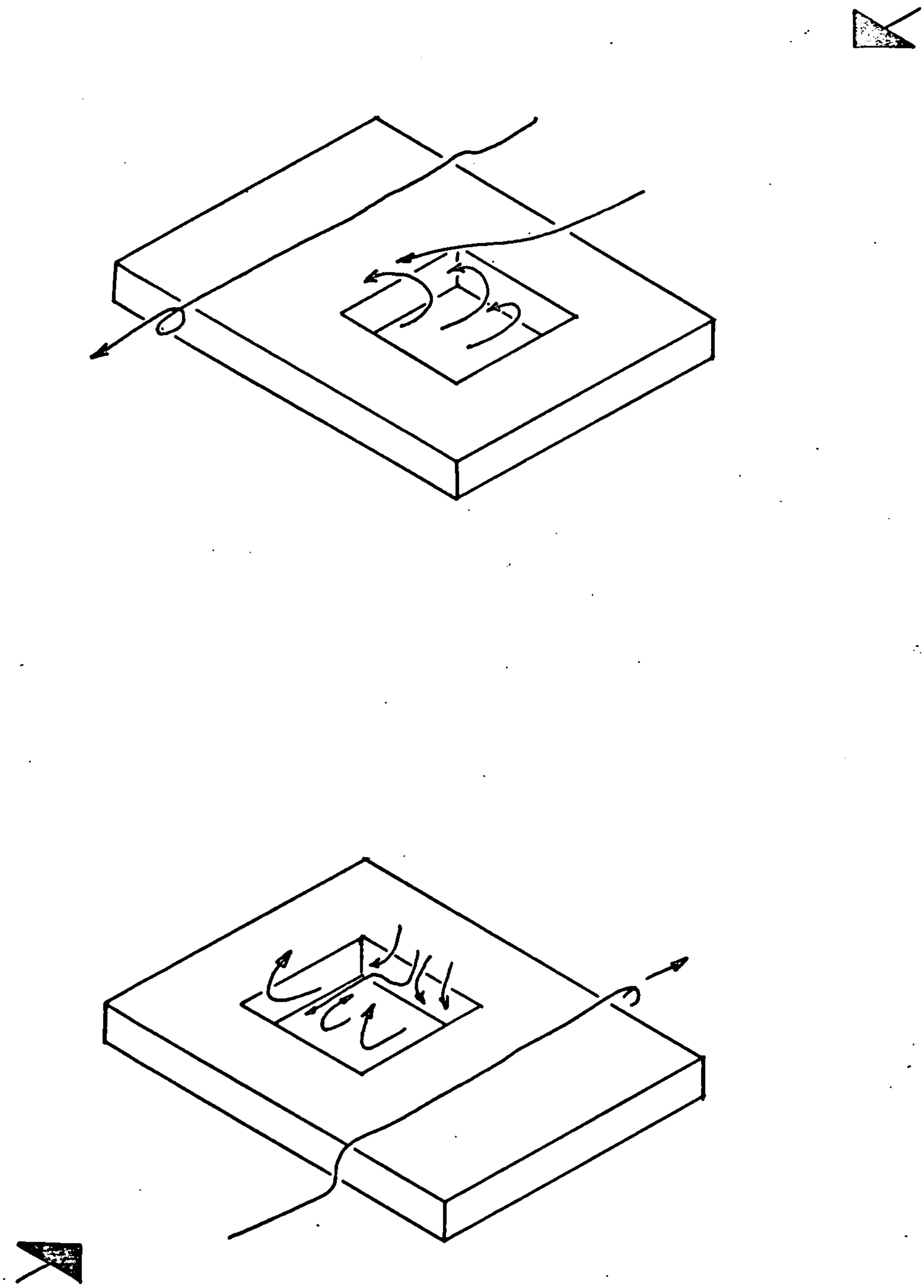


FIG 171 : GEOM 18 : WIND 270°

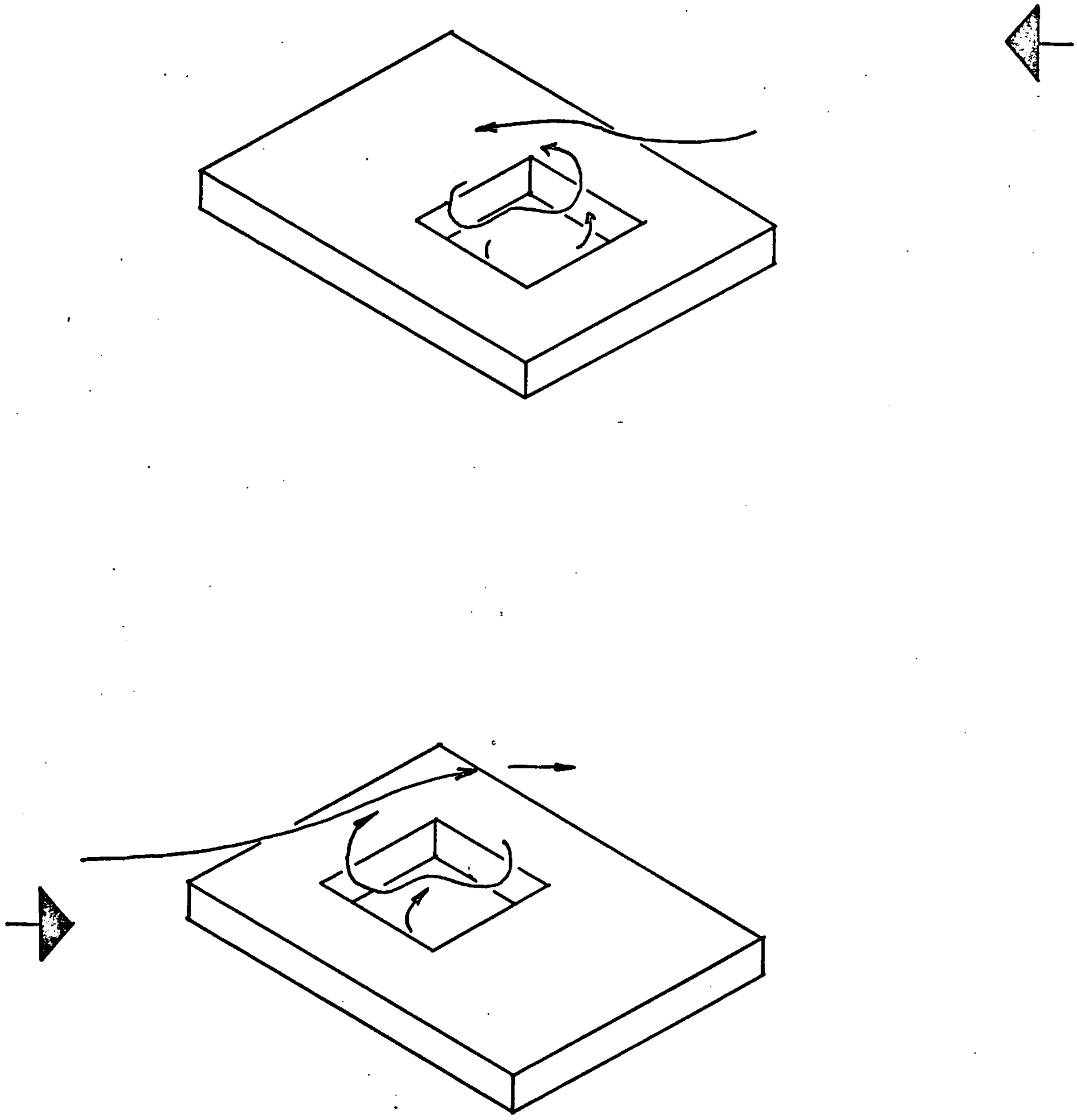


FIG 172 : GEOM 18 : WIND 225°

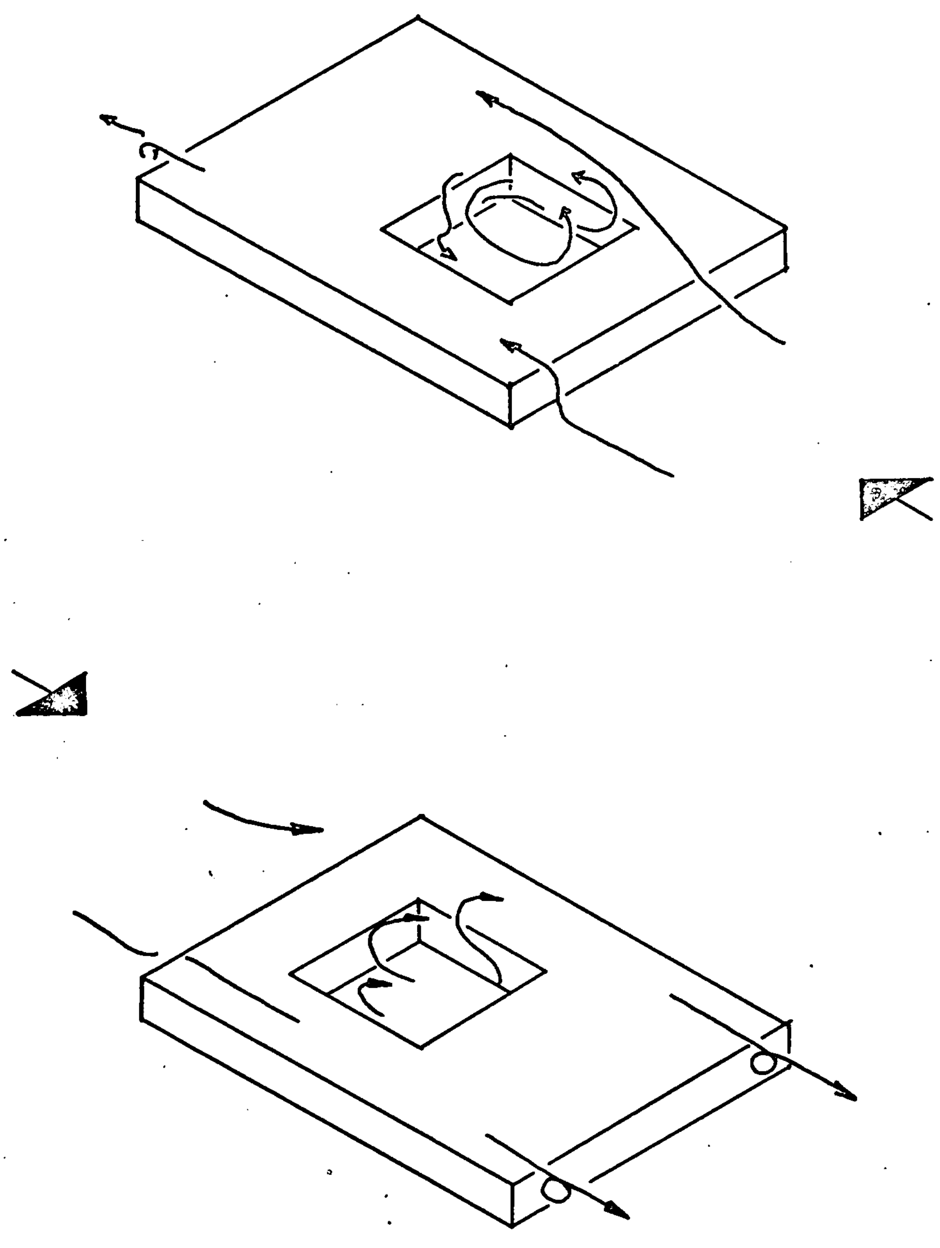
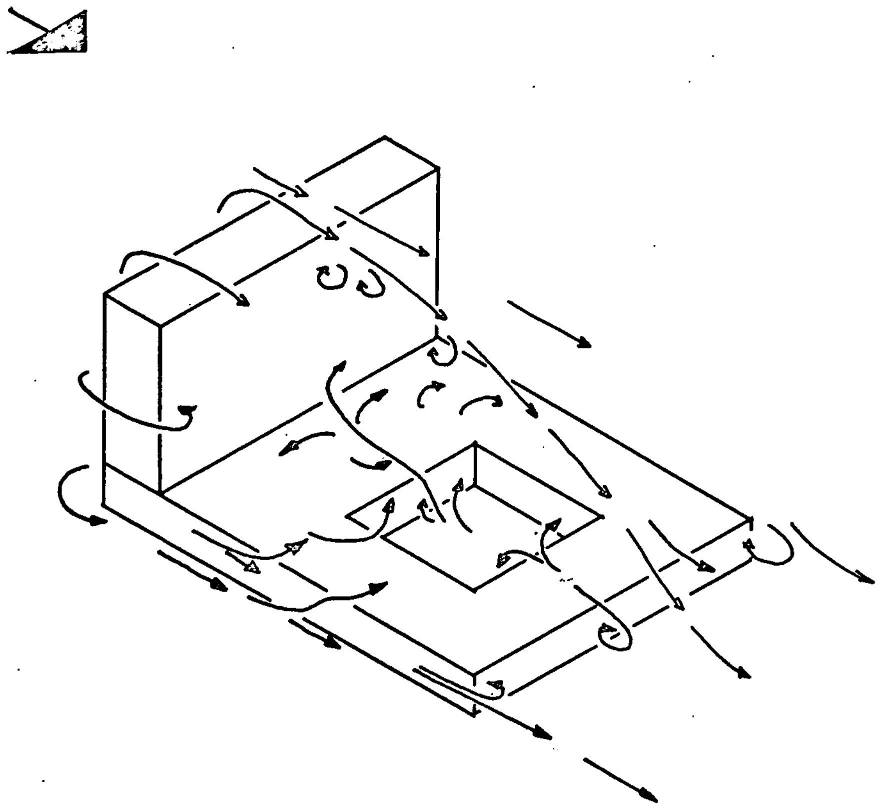


FIG 173 : GEOM 18 : WIND 180°



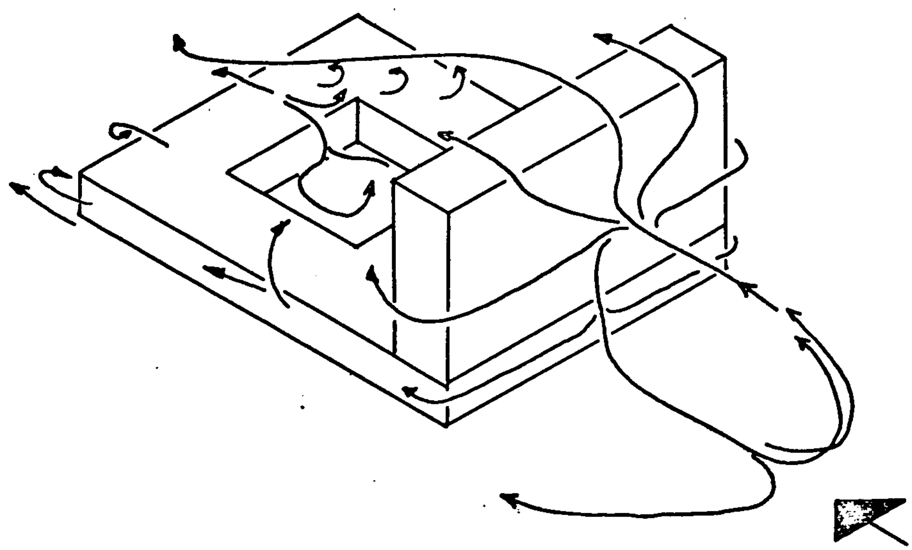
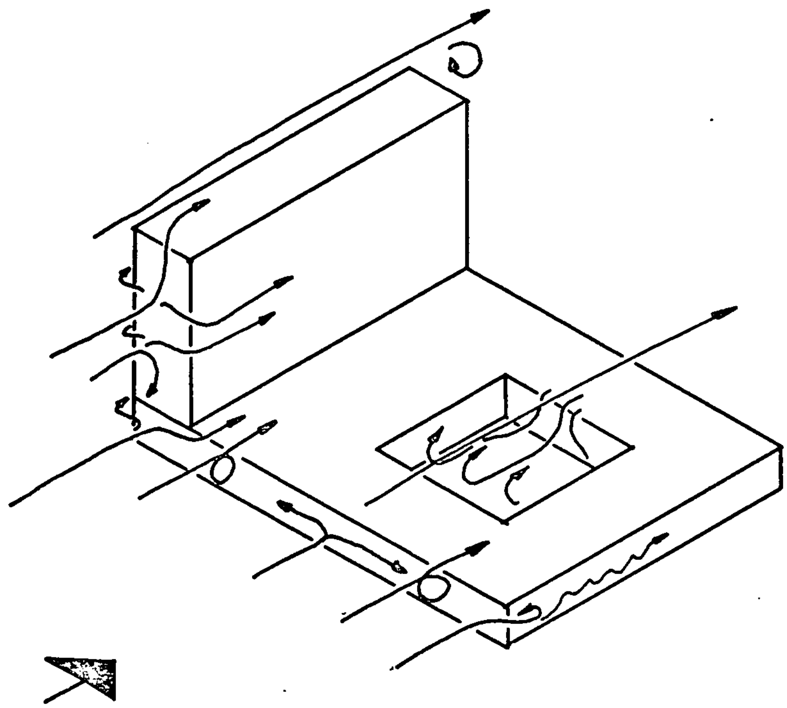


FIG 174 : GEOM 19 : WIND 0°



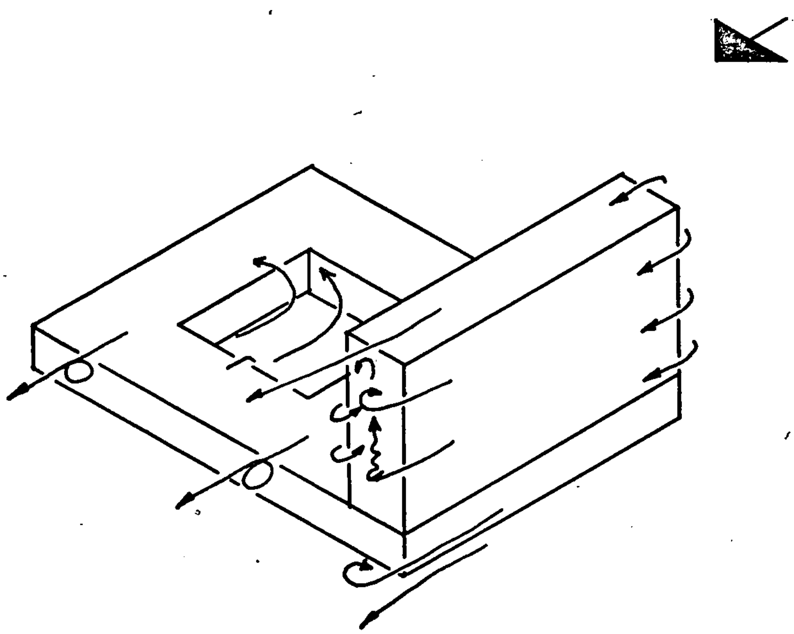


FIG 175 : GEOM 19 : WIND 90°

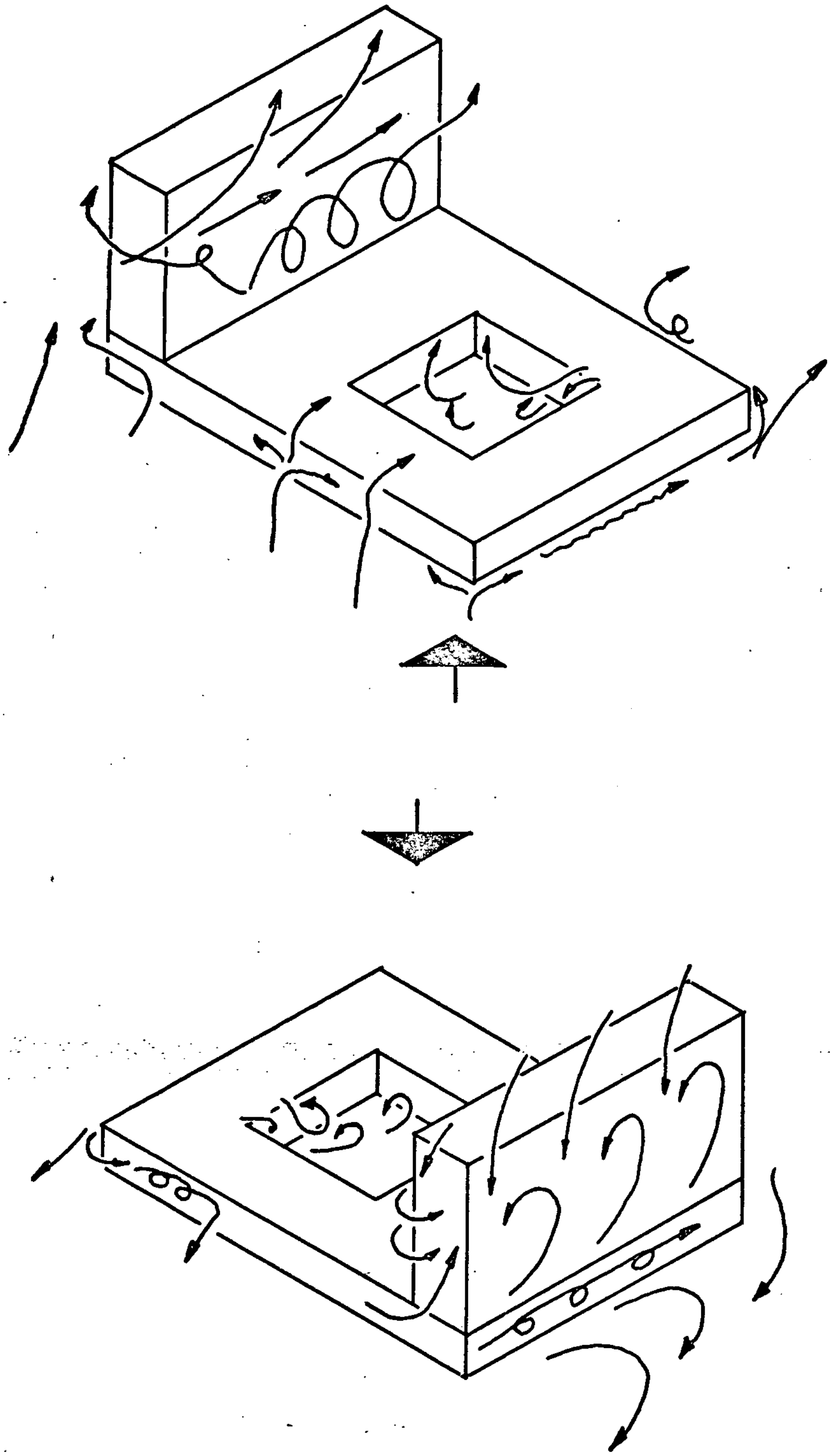
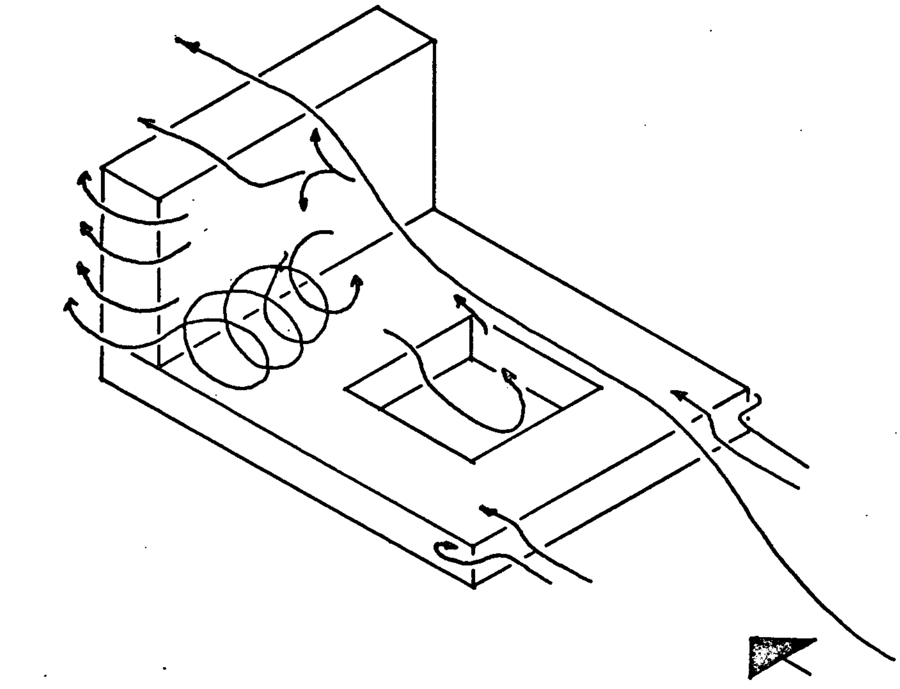


FIG 176 : GEOM 19 : WIND 135°



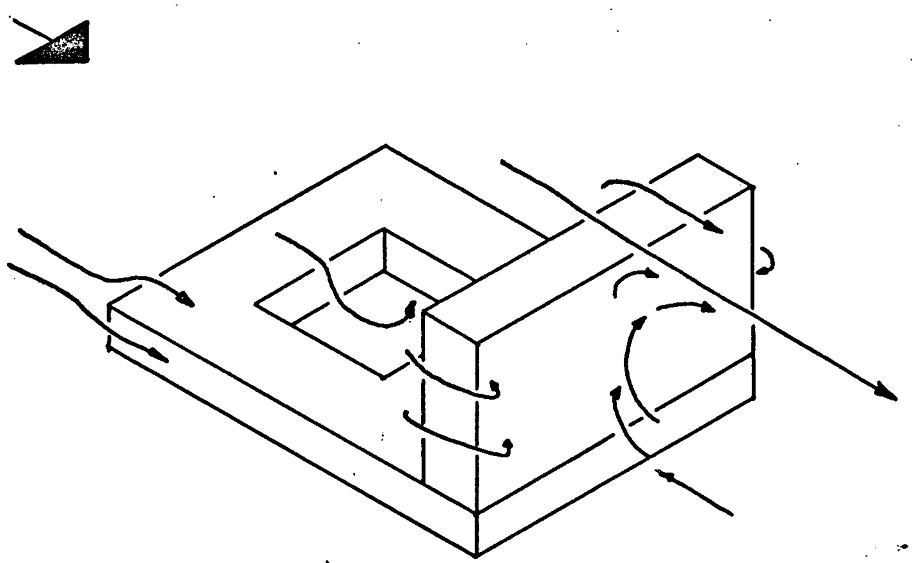
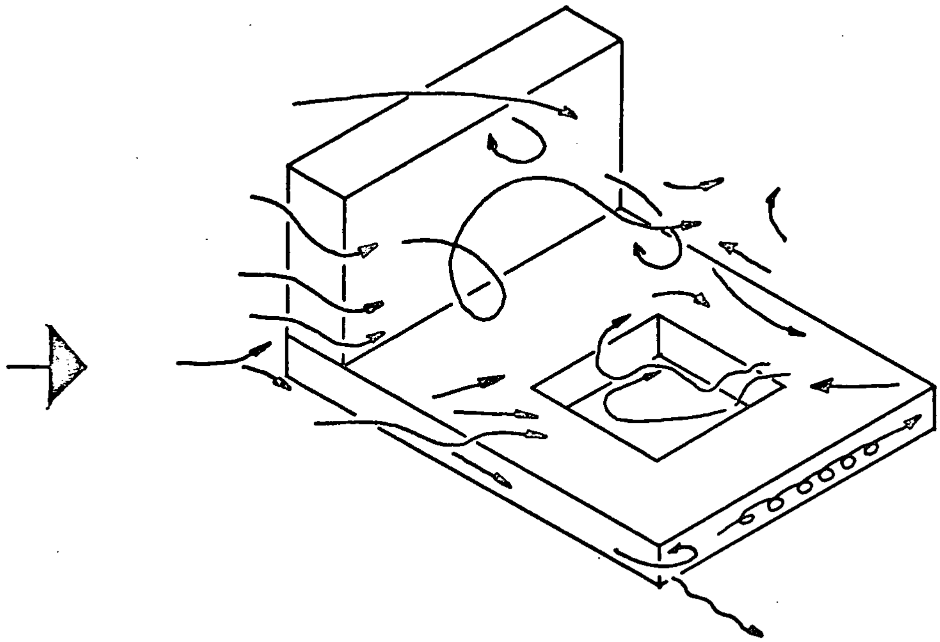


FIG 177 : GEOM 19 : WIND 180°



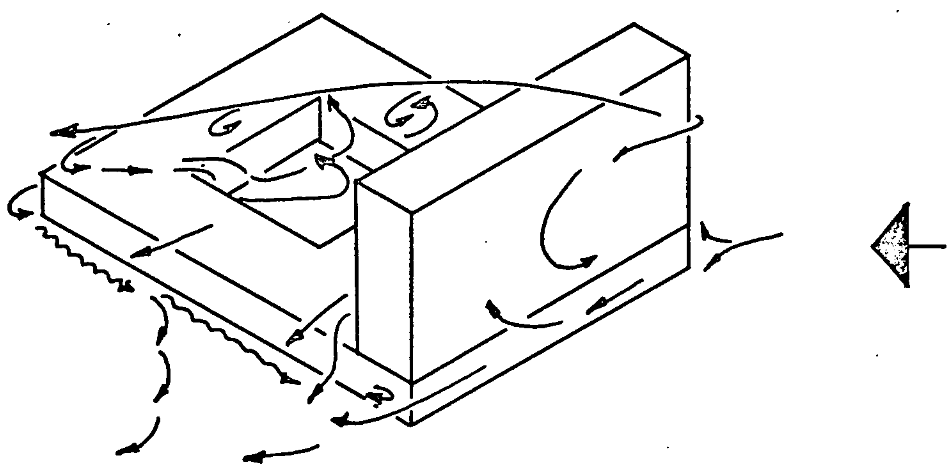
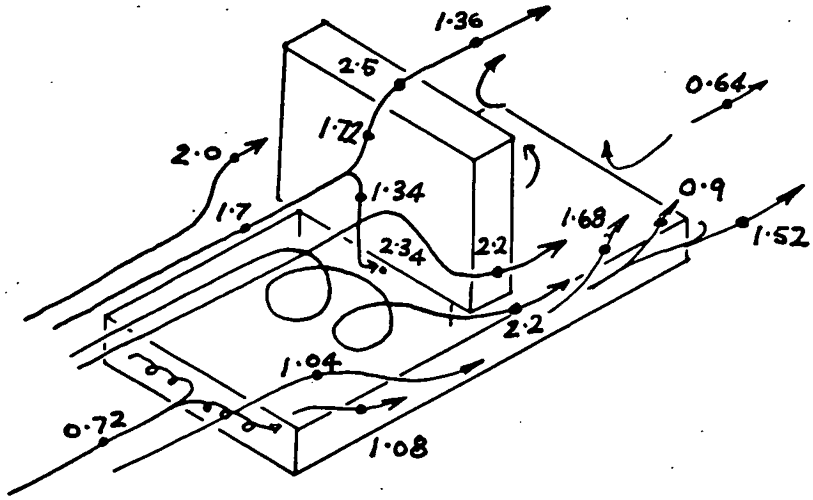


FIG 178 : GEOM 19 : WIND 45°



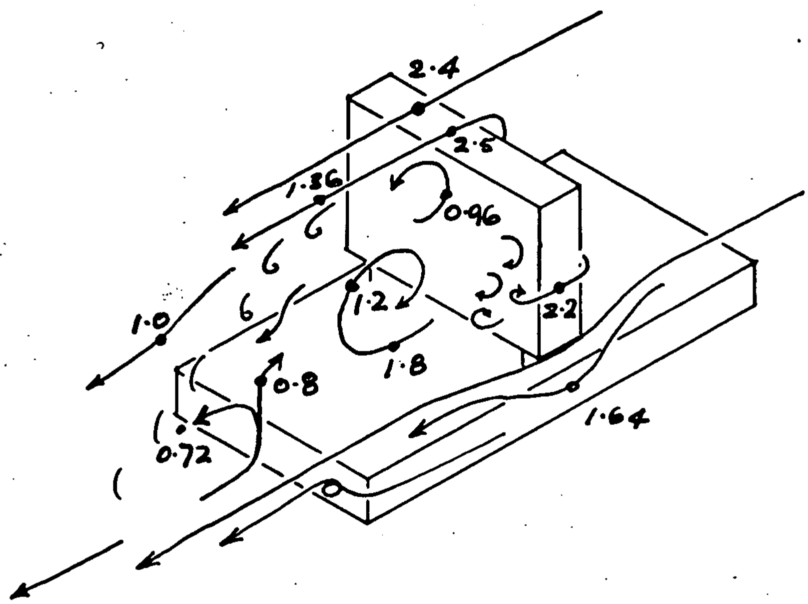


FIG 179 : GEOM 14 : WIND 0°

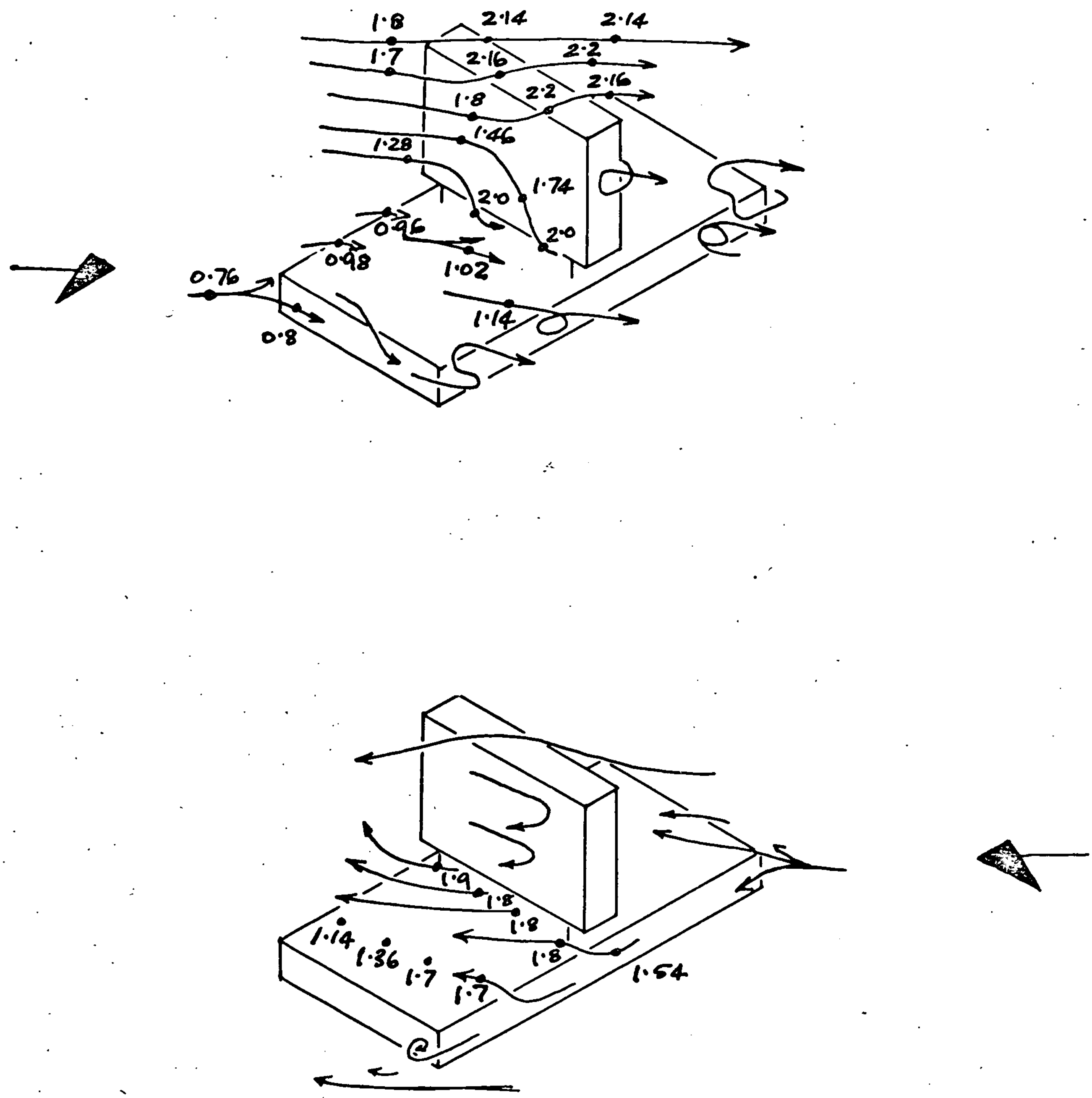


FIG 180 : GEOM 14 : WIND 315°

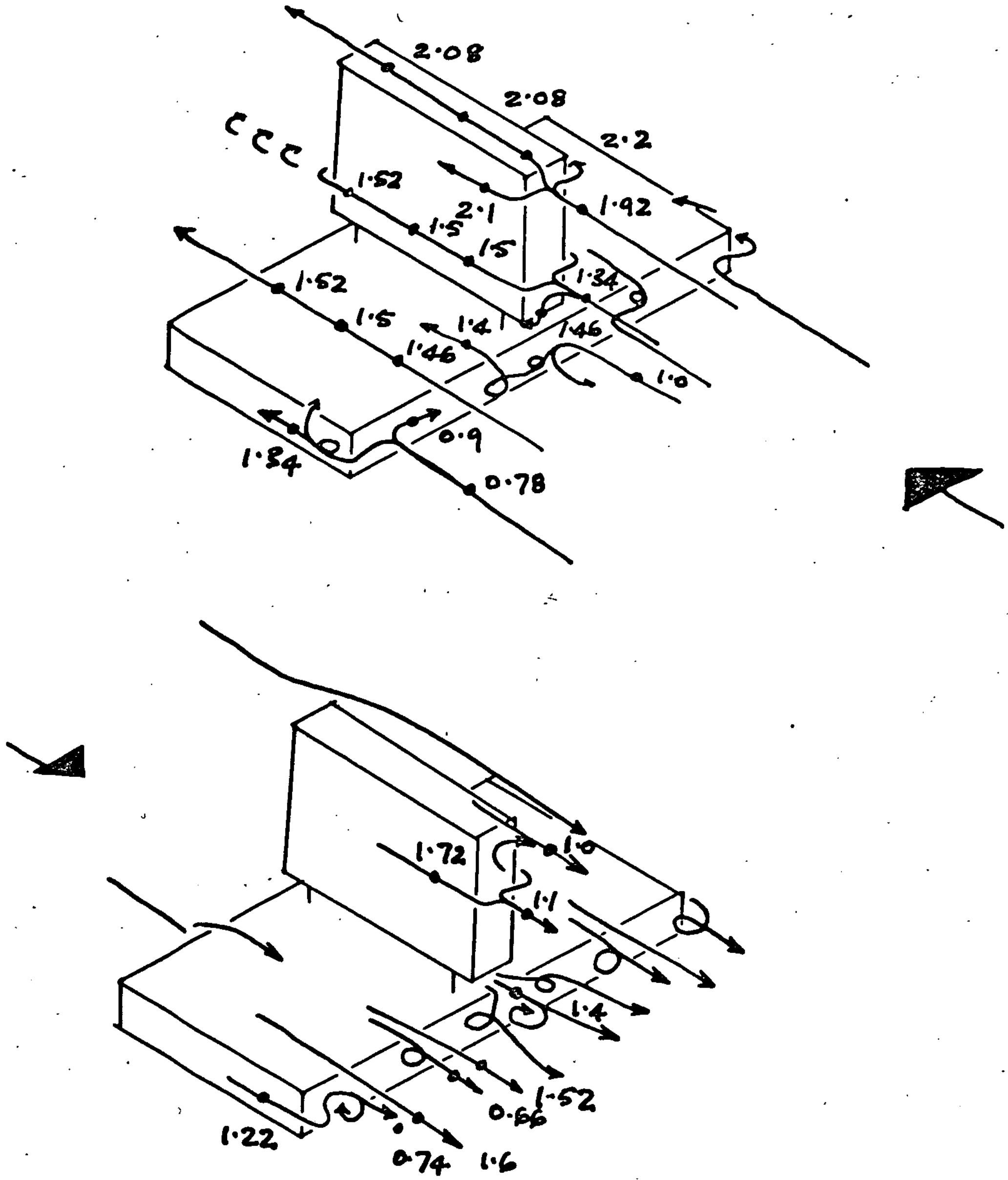


FIG 181 : GEOM 14 : WIND 270°